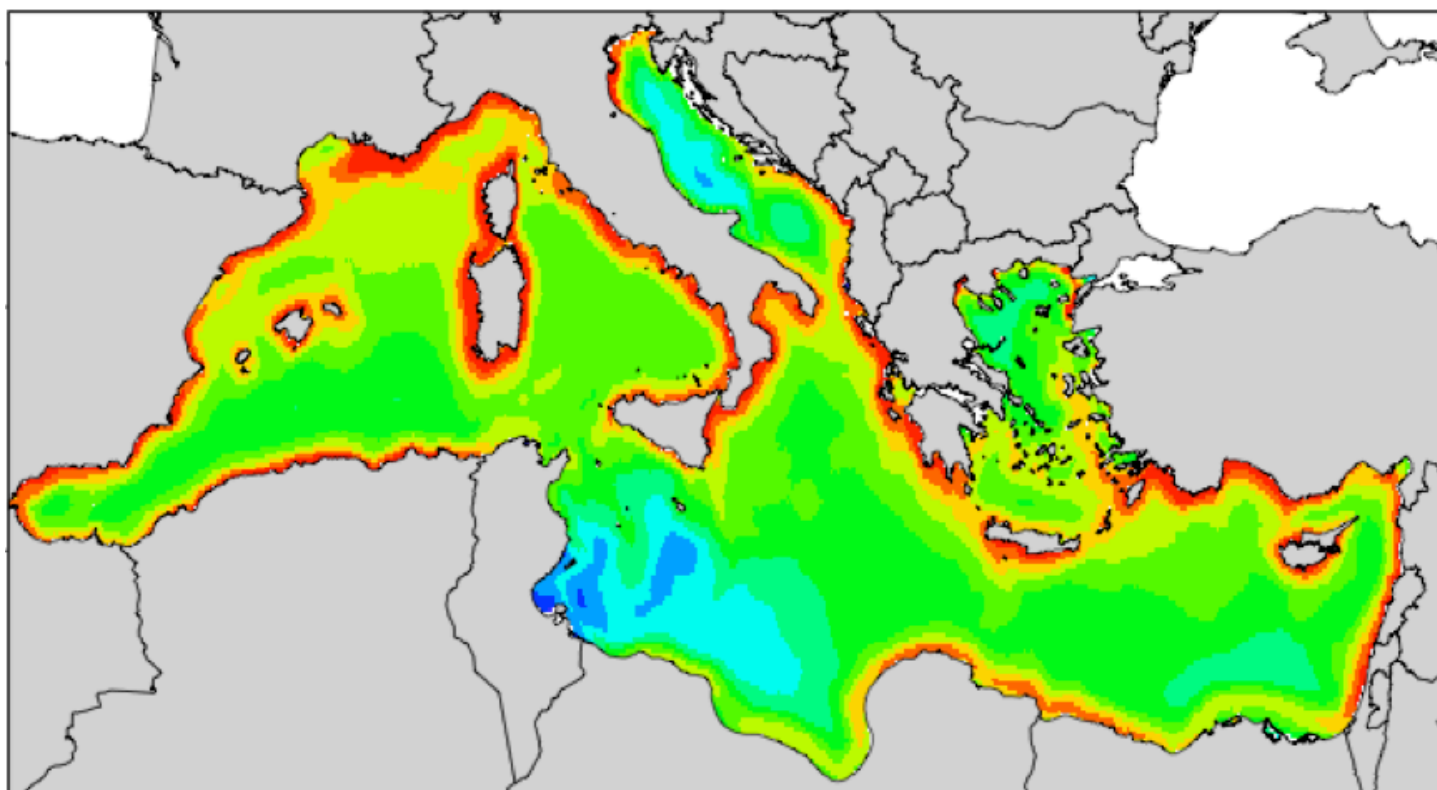


## JRC TECHNICAL REPORTS

# Alternative assessments of large scale Eutrophication using ecosystem simulations: hind-casting and scenario modelling

Adolf Stips, Diego Macias, Elisa Garcia-Gorriz,  
Svetla Miladinova

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## Abstract

The Marine Strategy Framework Directive (MSFD) aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020, and to protect the marine resources upon which economic and social activities depend.

The progress achieved in marine modelling gives the possibility of more realistic simulations of many aspects of the marine environment. Therefore, now the use of marine modelling can support the assessment process of the marine environment as foreseen in the MSFD by defining baselines, addressing data gaps and allowing for scenario simulations. We are here focusing on demonstrating the usefulness of ecosystem model data for assessing eutrophication aspects, as covered by MSFD descriptor D5. The assessments are based on calculating indicators, namely first the long established trophic indicator TRIX and for comparison the more recent HEAT indicator (as applied by HELCOM).

We show that the use of ecosystem model data allows identifying sensitive areas and assessing long term trends in the development of eutrophication in 2 major European water bodies. Specifically strong spatial gradients from the open sea to the coast are detected in many variables and indicators. The available high resolution of the simulations allows the identification of such spatial gradients. The investigation of long term trends points to slightly increasing eutrophication problems in the Mediterranean Sea and the Baltic Sea. This increasing eutrophication trend seems to be caused by increasing nitrate concentrations in the Mediterranean Sea. In contrast, in the Baltic Sea the increase in TRIX and HEAT indicators seems to be due to increasing phosphate concentrations.

We performed scenario simulations for investigating the impact from changing climate variability and from reducing nutrient inputs in the Mediterranean Sea. According to the model results, reduced climate variability (by using climatological atmospheric forcing) would lead to increasing eutrophication problems in many coastal regions and especially in the Aegean Sea. The proposed nutrient reduction scenario achieves surprisingly minor overall improvements, which are clearly identifiable only in the Adriatic Sea and the Aegean Sea, regions actually suffering from the most pronounced nutrient inputs. Finally possible methodological improvements and a way forward are discussed.

We conclude that further nutrient reductions in the Mediterranean Sea and in the Baltic Sea will be necessary to reduce the eutrophication impact on marine and coastal ecosystems. However, it seems illusionary to aim at fully restoring past ecosystems, rather ecosystem management should develop iterative adaptation strategies to deal with shifting baselines and to maintain ecosystem services at a sustainable level.

# 1. Introduction

Eutrophication is an environmental issue of concern, since it has been and is one of the major water quality problems in lakes, reservoirs, coastal zones and the marine environment in many parts of the world. The problem of eutrophication is also concerning the obligation of the Member States to assess the environmental state of their marine areas and to establish a Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD), as eutrophication is one of the MSFD descriptors (D5). It is of course also of direct relevance to estuaries and coastal waters that fall under the regulation from the Water Framework Directive (WFD). Commission Decision 2010/477/EU states that human-induced eutrophication should be minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algal blooms and oxygen deficiency in bottom waters. The assessment of eutrophication in marine waters needs to combine information on nutrient levels and on a range of those primary effects and of secondary effects which are ecologically relevant, taking into account relevant temporal scales. Trophic conditions of European marine areas vary considerably with time and from region to region and within regions.

Current assessments of the eutrophication status (ES) are typically based on monitoring data (Fleming-Lehtinen 2015). However often data availability is scarce, not homogeneous in space and time and this makes comprehensive assessment and consistent regional comparisons difficult to achieve. Eutrophication assessment using data from state-of-the-art ecosystem models could be a potential method to overcome some of these difficulties and to achieve comparable assessments encompassing large areas as the Mediterranean Sea. Here we want to explore a large-scale approach using recent model data from a coupled hydrodynamic-ecosystem model for the Mediterranean Sea (Macias, 2014a, 2014b). Such an approach could help to address eutrophication problems in coastal zones and European regional seas using ecosystem modelling for assessment, baseline identification, indicator development and scenario building. However it should be clear that assessments based on simulated data could only provide additional information in support of assessments based on measured data.

Nixon (1995) defined Eutrophication broadly as **an increase in the rate of supply of organic matter in an ecosystem**. First assessments using this definition were based only on chlorophyll-a measurements. This definition is however missing the consequences of the increased nutrient supply and is therefore not suitable from a management perspective.

A now widely accepted definition of eutrophication is based on OSPAR, (2008): *"Eutrophication means the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned,..."*

Based on that definition several methods using monitoring data have been proposed and are currently applied, as the "OSPAR comprehensive method", the HELCOM Eutrophication Assessment Tool (HEAT), the Trophic Index (TRIX) developed for the Mediterranean Sea and many others. Legislation as represented by the MSFD (COM DEC 2010/477/EU) for Descriptor 5 (eutrophication) enforces the already mentioned parameters (nutrients, chlorophyll, transparency and dissolved oxygen) plus additional parameters (opportunistic macroalgae, floristic species shift, seagrass abundance) to be used as indicators. For this methodological orientated study we focus on indicators that apply quantitative measures to physical, chemical and biological variables that can be



measured easily and do also represent common variables used in lower trophic level ecosystem models (excluding therefore higher trophic levels).

The HELCOM Eutrophication Assessment Tool (HEAT) as well as other indicators used for assessing eutrophication (for example TRIX, Vollenweider et al. (1998)) are usually based on measured quantities of the by the OSPAR definition mentioned variables. As however measured data often do have large gaps in space and time they cannot provide a comprehensive picture of the investigated ecosystem. We propose here to use model data from carefully validated ecosystem models to perform an additionally or complementary eutrophication assessment applying basically the same procedure as used with measured data. Because of the better temporal and spatial coverage, this approach could help to identify sensitive regions and critical time periods. It could also support the identification of trends and to detect relevant data gaps in the monitoring program. Contrary to the real world computer models provide the possibility to perform scenario simulations, which could allow answering "what if" questions.

## 2. Objectives of this work

Here we want to demonstrate the feasibility of assessing large scale eutrophication features using data from ecosystem model simulations. Therefore the main objective of this work is the identification of relative changes in the eutrophication state (temporal and spatial trends and hot spots) in large marine water bodies and is not on the calculation of absolute calibrated eutrophication indicators. This work cannot replace but could only give additional support for eutrophication assessments based on measured data and on agreed target values. Furthermore, this model based approach gives the possibility to create and investigate hypothetical scenarios, including different baselines.

The specific objectives of this work are summarised as follows:

- Provide a brief background of the used ecosystem models.
- Present the methodology for calculating TRIX and HEAT indicator
- Adapt the methodology to be used (in a consistent way) with ecosystem model data.
- Apply the TRIX and HEAT methodology on base line data from ecosystem model simulations.
- Apply these methods to two different water bodies, the Mediterranean Sea and the Baltic Sea.
- Investigate potential long term trends of these indicators.
- Investigate potential spatial trends of these indicators.
- Identify potential causes of identified trends.
- Compare base line simulation to a climate variability scenario.
- Compare two different nutrient input scenarios.
- Propose potential methodological improvements and calibration.
- Propose a way forward, especially how to achieve a harmonization with existing procedures based on measured data (HELCOM).

### 3. Methodology: TRIX and HEAT (ER/ES) indicators

Comprehensive eutrophication assessment is currently based on indicators that comprise 3 distinct features of eutrophication namely:

- 1) First the causes, as nutrient levels (DIN and DIP),
- 2) Second the direct effects (primary productivity, chlorophyll, clarity),
- 3) Third the indirect effects (oxygen levels or effects on higher trophic levels).

In the following we only consider such indicators that cover all these 3 fundamental characteristics. Numerous different concepts and indicators have been developed for the different European Seas. For this investigation we select the trophic index TRIX as it is one of the first indicators developed that is based on the above mentioned principles. Higher trophic level indicators will not be included here, due to the lack of data on higher trophic levels in most ecosystem models. First we apply the TRIX concept to quasi realistic ecosystem simulations of the Mediterranean Sea. In order to test the wider applicability of this approach we further apply TRIX also to the Baltic Sea and compare it there to calculations based on the HELCOM HEAT procedure for calculating the Eutrophication Ratio (ER).

#### 3.1 Trophic Index TRIX

Using measured data from the Adriatic Sea Vollenweider et al. (1998) proposed a trophic index (TRIX) based on total nitrogen and total phosphorus, chlorophyll-a and oxygen saturation to characterise the trophic state of coastal marine waters. In developing the TRIX they observed the following principles:

- the component variables of the index should be meaningful in terms of both production and production dynamics;
- they should encompass major causal factors;
- they should encompass major disturbances;
- they should be routine measurements in most marine surveys.

The trophic state depends on the availability of nitrogen and phosphorus for primary production, which in turn determines the phytoplankton biomass and oxygen saturation. In TRIX the nutrients are represented ideally by total nitrogen and total phosphorus; chlorophyll-a is a substitute parameter for phytoplankton biomass, as production is not routinely measured; and the deviation of oxygen saturation from 100% (aD%O) in the productive layer indicates the production intensity of the system. This encompasses both phases of active photosynthesis and phases of prevailing respiration. Already in his original paper Vollenweider et al. (1998) proposed to consider water turbidity (Secchi depth) as an additional measure and combined both measures into a general water quality index. They argued however, that water transparency should not be incorporated into TRIX, because it incorporates also mineral turbidity which is not relevant to eutrophication. As primary production is mainly determined by the presence

of bioavailable nutrient forms, we replace total nitrogen and phosphorus by Dissolved Inorganic Nitrate (DIN) and Dissolved Inorganic Phosphate (DIP).

The variables used in the calculation must be made non-dimensional and scaled in order to combine them into a single indicator. Here we chose to apply a scaling covering a wide range of possible values.

Variable	Unit	Lower	Upper	
<b>DIN</b>	[mmol m <sup>-3</sup> ]	0.001	60	
<b>DIP</b>	[mmol m <sup>-3</sup> ]	0.001	10	
<b>Chla</b>	[mg m <sup>-3</sup> ]	0.01	60	
<b>aD%O</b>	[%]	0.1	100	
<b>PPR</b>	[mmol m <sup>-3</sup> d <sup>-1</sup> ]	0.05	5.0	

**Table 1 Selected range for scaling of selected variables**

The chosen minimum and maximum values should encompass most of the natural variability found in the European regional seas. Further it should be ensured that smaller values as the selected minimum will not represent a further significant improvement as well as larger values than the selected maximum will not mean a significant further degradation. The TRIX indicator is then calculated as the sum of the selected log-transformed and scaled variables according to the following principle.

$$TRIX = \frac{k}{n} \sum_{i=1}^n \frac{(\log M - \log L)}{(\log U - \log L)} \quad (\text{Eq. 1})$$

n = number of the variables (in our case four), M = measured value of the variable, U = upper limit, L = lower limit. The scaling factor k could be freely selected, we chose k=1.

$$TRIX = \log(\text{Chla aD\%O DIN DIP}) \quad (\text{Eq. 2})$$

For the purpose of this study surface mean values (0-20m) are used. Contrary to other work we will use data generated by an ecosystem model.

Generally higher TRIX values indicate a bad eutrophication state and lower values are considered as better (less eutrophic). Throughout this study we focus on relative changes and trends, thereby avoiding potential problems resulting from model calibration inaccuracies. The assumption of an absolute trophic scale might have relevance for some specific regions, but is generally questionable. We therefore do not consider here absolute TRIX values as relevant, but are rather looking at trends and relative comparisons. Further also MSFD and WFD frame ecological assessments with respect to site specific reference conditions.

## 3.2 HELCOM Eutrophication Assessment Tool - HEAT

HELCOM has based the development of an eutrophication indicator (HEAT) for the Baltic Sea on the same principles as already proposed by Vollenweider 1998 that can be combined to provide one overall picture of eutrophication.

The core eutrophication indicators as developed by HELCOM comprise nitrogen, phosphorus, chlorophyll-a, water clarity and oxygen. Here the meaning of oxygen has changed to "oxygen debt" below the halocline. HELCOM further uses predefined region-specific "indicator targets" (TARGREV project) that were set out by an expert evaluation process.

HEAT builds on the OSPAR Common Procedure developed for assessment and identification of 'eutrophication problem areas' in the OSPAR convention area, in particular the North Sea, the Channel, the Skagerrak and the Kattegat (see OSPAR 2003, 2008). It also makes use of some of the key assessment principles of the WFD, e.g. the calculation of an Ecological Quality Ratio (EQR) and the 'one out, all out' principle (Borja et al. 2009). The average inorganic nitrogen and phosphorus concentrations at the surface (0 – 10 m depth) during the winter months (December to February) are used as indicators for nutrient levels.

The average chlorophyll-a concentration at the surface (0 – 10 m depth) from June to September is the only indicator describing the amount of algae, which together with Secchi depth expresses the direct effects of eutrophication. The months between June and September are in most areas considered to represent the summer period after the spring bloom, which typically occurs between March (southern part) and May (northern part).

Average summer (June – September) Secchi depth is used to describe water clarity. Water clarity, especially where it can be related to changes in algal biomass, is regarded as a direct effect of eutrophication. However, Secchi depth is a complex indicator also expressing non-eutrophication related signals

In the original HEAT an oxygen debt indicator represents indirect effects of eutrophication. The bottom oxygen debt indicator describes deviation from natural oxygen levels. As this is however very specific for the Baltic Sea and in order to remain better compatible to the already presented TRIX indicator we use here instead the oxygen deviation from saturation, as used in calculating the TRIX indicator. The principal feasibility of reliably calculating the bottom oxygen debt indicator remains to be demonstrated, considering the large uncertainty of this quantity.

The average or weighted average of Eutrophication Ratio (ER) values within an indicator category is denoted the category-specific ER (see Fleming-Lehtinen *et al.*, 2015, for details). The value 1.00 represents roughly the boundary for assessing whether an indicator group shows an area to be affected or unaffected. Areas with values <1.00 are regarded as 'unaffected by eutrophication', while areas with values  $\geq 1.00$  are considered impaired and 'affected by eutrophication'.

The usual applied "one out = all out" principle for calculating ES is appropriate to estimate the state of eutrophication in the system under consideration, however it is not useful for calculating temporal or spatial trends. As the focus of this work is not on the calculation of an absolute calibrated eutrophication indicator, but rather on the identification of relative changes (temporal and spatial trends and hot spots), this principle is not applied to the here presented indicators.

## 4. Applied Modelling System

### 4.1 Mediterranean Sea ocean model

The 3-D General Estuarine Transport Model (GETM) was used to simulate the hydrodynamics in the Mediterranean Sea. GETM solves the three-dimensional hydrostatic equations of motion applying the Boussinesq approximation and the eddy viscosity assumption (Burchard and Bolding, 2002). A detailed description of the GETM equations could be found in Stips et al. (2004) and at <http://www.getm.eu>.

The configuration of the Mediterranean Sea (Fig. 1) has a horizontal resolution of 5' x 5' and includes 25 vertical layers. ETOPO1 (<http://www.ngdc.noaa.gov/mgg/global/>) was used to build the bathymetric grid by averaging depth levels to the corresponding horizontal resolution of the model grid. The salinity and temperature climatologies required at the start of the model integration were obtained from the Mediterranean Data Archeology and Rescue-MEDAR/MEDATLAS database (<http://www.ifremer.fr/medar/>) while biogeochemical initial and boundary conditions were computed from the World Ocean Atlas database ([www.nodc.noaa.gov/OC5/indprod.html](http://www.nodc.noaa.gov/OC5/indprod.html)). All model runs described below started with exactly the same initial conditions.

Boundary conditions at the western entrance of the Strait of Gibraltar were also computed from the same MEDAR/MEDATLAS dataset imposing monthly climatological vertically-explicit values of salinity. Sea surface temperature at the western entrance of the Strait were extracted from the nearest node of the driven GCM for each simulation (see below). No horizontal currents were imposed at the open boundary. With this boundary configuration the circulation through the Strait is stabilised by the internally-adjusted baroclinic balance provoked mainly by the deep-water formation within the basin (Macias et al., submitted). Although the magnitude of the interchanged flow and horizontal velocities in Gibraltar are in agreement with observations (not shown) the circulation pattern within the Alboran Sea is not in concordance with measurements as the eastern gyre is typically weaker than expected (Macias et al., 2015).

The GETM configuration for the Mediterranean Sea is forced at surface every 6 hours by the following atmospheric variables, wind velocity at 10 meters (U10 and V10), air temperature at 2 m (T2), dewpoint temperature at 2 m (D2), cloud cover (TCC) and sea level pressure (SLP) provided by the different realizations of the atmospheric model described in the next section. Bulk formulae are used to calculate the corresponding relevant heat, mass and momentum fluxes between atmosphere and ocean (Macias et al., 2013).

### 4.2 Biogeochemical model - Mediterranean Sea

The Ecological Regional Ocean Model (ERGOM, Neumann, 2000) was selected as the initial framework to represent the biogeochemical characteristics of the Mediterranean Sea. This model originally incorporates three macronutrients (nitrate, ammonium and phosphate), three phytoplankton types (diatoms, flagellates and cyanobacteria), one zooplankton variable (representing model closure), detritus, dissolved oxygen and a sediment compartment (coupled to the pelagic one through sedimentation and resuspension processes) (Neumann et al., 2002). The internal conversion currency of ERGOM is based on nitrogen units, and the balance of phosphorus and oxygen is based

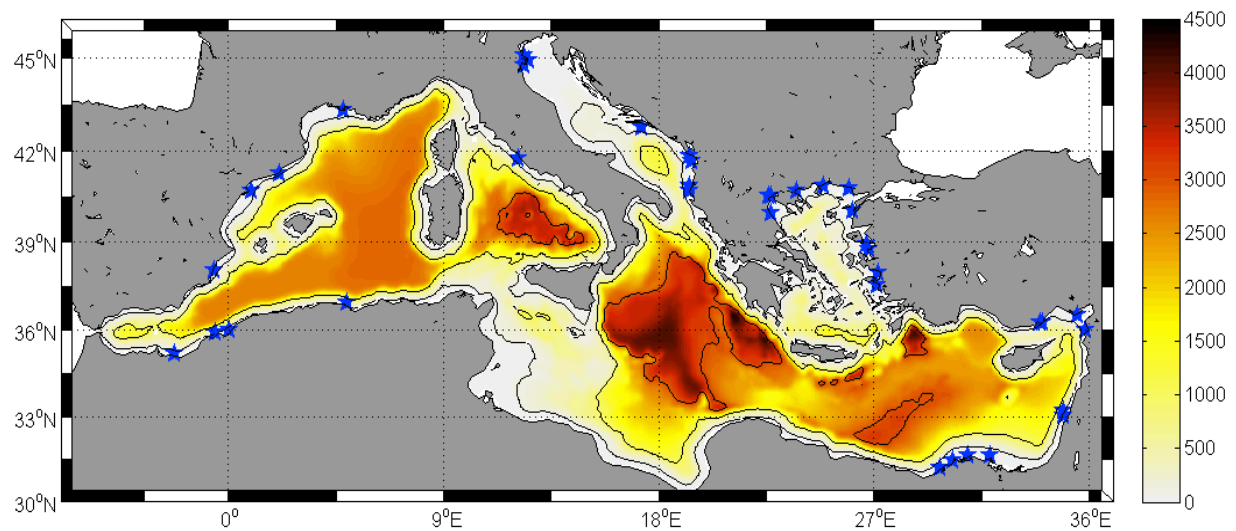
on nitrogen, using stoichiometric Redfield ratios. This model is, initially, adequate to represent the two main pathways for food and energy transfer in the Mediterranean; the classical herbivores-carnivores food path usually present in eutrophic regions and the small-sized microbial community more usual in the open-sea regions (Siokou-Frangou et al., 2010). Also, this model is able to take into account the limitation by different macronutrients such as nitrate, ammonia and phosphate as the maximum growth rate of phytoplankton groups are modulated by the relative concentration of each nutrient (Neumann, 2000). This is especially important for representing the Mediterranean basin as nitrate is usually limiting planktonic production in the western Mediterranean (e.g., Macias et al., 2009) while phosphate becomes limiting eastwards (e.g., Siokou-Frangou et al., 2010).

However, and in spite of being a potentially suitable candidate to represent the Mediterranean ecosystem, ERGOM was initially created and further developed to simulate the Baltic Sea, which has some obvious differences with the Mediterranean. Henceforth, and besides changing the values of several parameters, we needed also to modify and tailor the ERGOM code to our study site. As this model has been extensively described in several references in the literature (e.g., Burchard et al., 2006; Neumann, 2000; Neumann et al., 2002) we will focus here on the specific modifications made on its original implementation to adapt this model to the Mediterranean ecosystem (MedERGOM). Zooplankton mortality losses were modified by including two linear expressions (excretion and mortality) and a quadratic term (predation) following the recommendations for the Mediterranean Sea provided by Oguz et al. (2013). The predation term is treated as the closure of the model and, thus, is lost from the system. The light limitation of primary production was also changed in this implementation of MedERGOM. Instead of using a single set of light limitation values for all three phytoplankton types, specific values of the production irradiance curves were adopted for each functional type (Follows et al., 2007). The functional response of growth rate to light levels was also changed following Wan and Bi (2013). More details and the calibration/validation of the model are described in Macias et al. (2014a).

### 4.3 Mediterranean Sea model implementation

All model runs for the Mediterranean Sea have been made with the exact same configuration, only atmospheric forcing and nutrient loads in rivers have been changed in the different scenarios. The common configuration of the ocean model is the same as described in Macias et al. (2013) with a horizontal resolution of 5' x 5' and using 25 vertical layers. ETOPO1 (Amante and Eakin, 2009) is used to build the bathymetric grid by averaging to the corresponding horizontal resolution of the model grid. The salinity and temperature climatologies required at the start of model integration were obtained from the Mediterranean Data Archaeology and Rescue-MEDAR/MEDATLAS database (<http://www.ifremer.fr/medar/>). The Strait of Gibraltar is prescribed as an open boundary and the Dardanelles inflow is treated as a riverine inflow within the basin. The current configuration of the model includes 37 rivers discharging along the Mediterranean coast with freshwater flows derived from the Global River Data Center (GRDC, Germany) database.

The biogeochemical model is coupled online to the hydrodynamic one via the Framework for Aquatic Biogeochemical Model (FABM, Burchard et al., 2006). This is a two-way coupled model system where hydrodynamics modifies biogeochemistry by water movement, substance transport, light availability and temperature dependence of process rates while biogeochemistry influences water column properties through light attenuation modifications by phytoplankton shelf-shading (Burchard et al., 2006).



**Figure 1 Bathymetry of the Mediterranean Sea**

#### 4.4 Baltic Sea model setup

Model simulations were performed using the hydrodynamic model GETM (General Estuarine Transport Model, [www.getm.eu](http://www.getm.eu)) coupled with the ERGOM (Ecological Regional Ocean Model, [www.ergom.net](http://www.ergom.net)) biogeochemical model. The ERGOM model version applied to the Baltic Sea contains 12 state variables: three phytoplankton groups (diatoms, flagellates and nitrogen-fixing cyanobacteria), nitrate, ammonium, phosphate, bulk zooplankton, detritus, dissolved oxygen, sediment detritus, iron-bound phosphorus in water and in the sediments. ERGOM uses nitrogen as a model currency. Nitrate, ammonium and phosphate are taken up by phytoplankton in accordance with Redfield nitrogen to phosphorus ratio 16:1. It is assumed that cyanobacteria are able to fix atmospheric nitrogen and are limited only by availability of phosphate. Ammonium and phosphate are released by respiration, excretion and detritus mineralisation. In the presence of oxygen, part of the ammonium is converted to nitrate through the process of nitrification. Under anaerobic conditions, and in the presence of nitrate, detritus is oxidised by reducing nitrate to dinitrogen gas which leaves the system. Under anaerobic conditions and depleted nitrate, hydrogen sulphide is produced through microbial use of oxygen bound in sulphate. The hydrogen sulphide concentration is counted as negative oxygen. In the case of oxic near-bottom conditions, a fixed portion of nitrogen recycled in the sediments is removed from the system through consecutive nitrification and denitrification. The model accounts for the oxygen-dependent dynamics of phosphate in sediments: under oxygenated conditions, part of the mineralised phosphate is forming iron-phosphate complexes which are stored in the sediments, whereas in anoxic conditions the previously stored phosphate is liberated to the overlying water. Detailed description and formulation of the model is given in Neumann (2000).

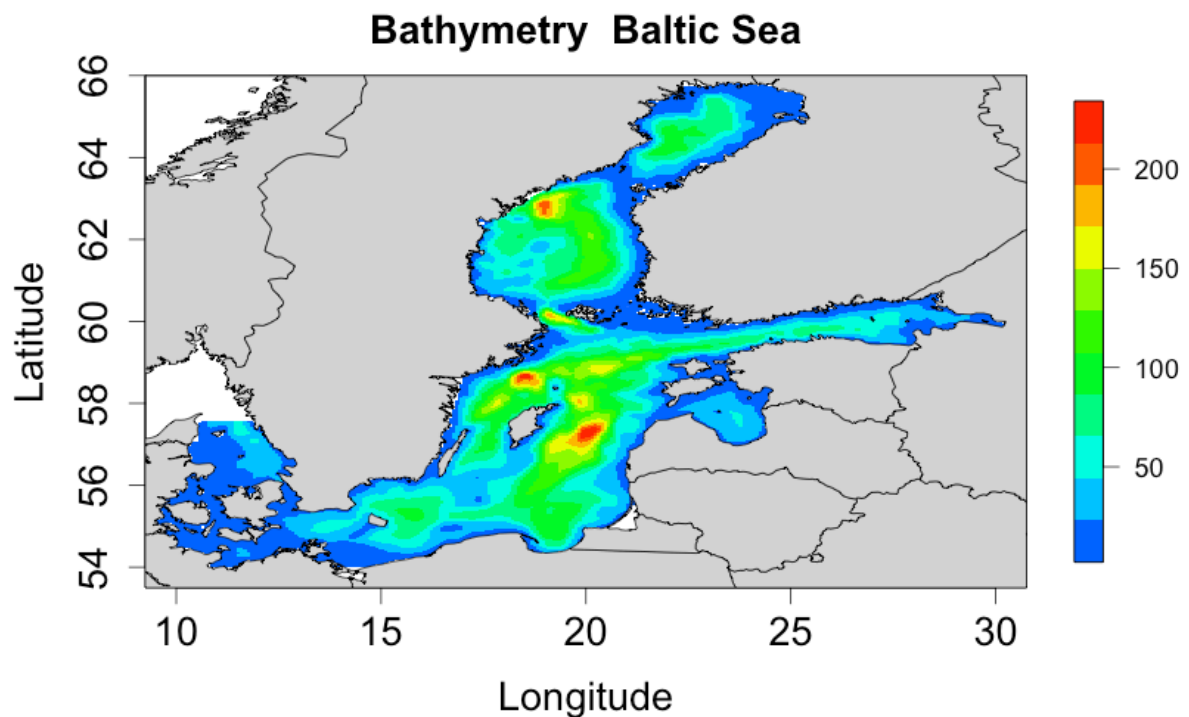
The model domain covers the entire Baltic Sea area with an open boundary in the northern Kattegat. Bathymetry was interpolated to a 2x2 nm (3704x3704 m) model grid from the digital topography of the Baltic Sea (Seifert et al. 2001). 25 layers were applied in the vertical, using adaptive coordinates. Adaptive coordinates are based on a vertical optimization of the layer distribution, which depends on vertical density and velocity gradients and the distance to surface and bottom, Hofmeister et al. (2011). The time step implemented is 30 s for the barotropic and 600 s for the baroclinic mode. The



period modelled is 01.01.1990–31.12.2009. During the first year of the simulation only hydrodynamics was modelled as a spin-up for the coupled hydrodynamic-biogeochemical simulation.

Initial distributions of water temperature and salinity for January 1990 were interpolated to the model grid from the monthly climatological data set provided by Janssen et al. (1999). Initial distributions of nitrate, ammonium, phosphate and dissolved oxygen were reconstructed from a limited amount of available measurement data covering the winter of 1991 and interpolated to the model grid. All the other biogeochemical model variables were given uniform initial distributions over the model domain based on previously reported typical winter values. Prescribed salinity and temperature distributions at the open boundary were interpolated using monthly climatological data. Hourly sea level fluctuations at the open boundary were interpolated from gauge measurements at Kattegat.

The model was forced with European Centre for Medium Range Weather Forecasting (ECMWF) ERA-Interim reanalysis meteorological data. The ERA-Interim configuration uses a 30 min time step and has a spectral T255 horizontal resolution, which corresponds to approximately 79 km spacing on a reduced Gaussian grid, Dee et al. (2011). The original data on air temperature, dew point temperature, air pressure, cloud cover, wind speed and wind direction, were interpolated to a regular Gaussian grid corresponding to approximately 50 km spacing with 6-hourly temporal resolution. The model took into account land-based runoff and nutrient loads which had been incorporated into 20 major rivers (Neumann and Schernewski, 2008). Atmospheric deposition of nutrients was taken constant over the entire modelled period.



**Figure 2 Bathymetry of Baltic Sea model setup**

## 5. Eutrophication assessment using ecosystem simulations in the Mediterranean Sea

The baseline run (R1\_RF\_RN or R1) uses the exact same external forcings (atmosphere and nutrients from rivers) as described in Macias et al. (2014b). This model run for the Mediterranean Sea is forced at surface every 6 hours with ECMWF reanalysis products. Specifically, we use the ECMWF ERA40 reanalysis products from 1957 to 1978 and the ERA-Interim products from 1979 to 2011 (available from <http://www.ecmwf.int>). The consistency of these data sets has been checked to avoid spurious results. Nutrient content (nitrate and phosphate) of freshwater runoff were obtained from Ludwig et al. (2009). Climatological values were used in case of missing data. Atmospheric input of nutrients was not included.

### 5.1 Statistics of ecosystem variables (TRIX input)

#### 5.1.1 General statistic

The general overview of the ecosystem variables statistics serves mainly to assess the validity of the chosen scaling (variable range). In the Mediterranean Sea the simulated mean surface concentration of nitrate is about 100 times higher than the mean phosphate concentration (Table 2). As the ratio of nitrogen to phosphorus found in phytoplankton in the ocean (Redfield ratio), in short N:P is only 16:1, this would lead hypothetically to the conclusion that the limiting nutrient in the Mediterranean Sea should be phosphate.

From the variable range found, we conclude that our chosen scaling ranges are appropriate.

Variable	Units	Min	Max	Median	Mean	Stdev
Nitrate	mmol m <sup>-3</sup>	0.1356	27.65	3.646	3.644	0.6072
Phosphate	mmol m <sup>-3</sup>	0.0040	1.149	0.0084	0.0302	0.0189
Chlorophyll	mg m <sup>-3</sup>	0.0017	4.806	0.1592	0.2506	0.1387
PPR	mmol m <sup>-3</sup> d <sup>-1</sup>	0.0206	81.08	0.0788	0.1992	0.1734
aD%O	[%]	0	90.11	3.134	3.365	1.647

Table 2 Statistics of simulated ecosystem variables (50 years)

### 5.1.2 Long term trends

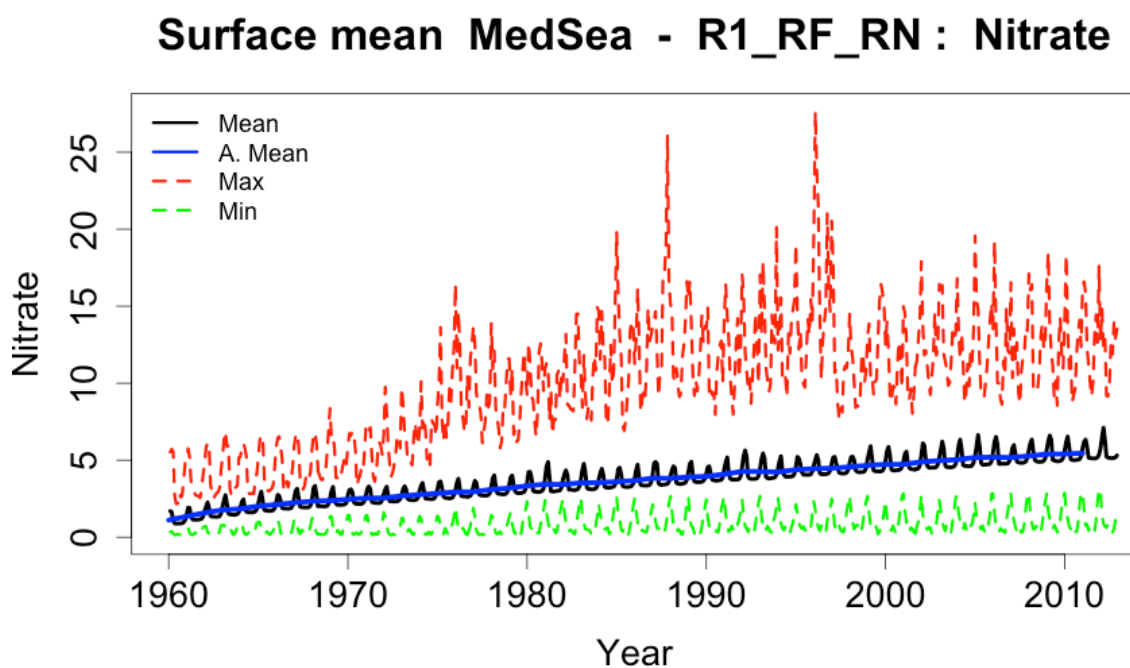
The availability of this long term simulation covering 5 decades allows for the evaluation of changes in the ecosystem composition.

Variable	Units	Trend	Conf
<b>Nitrate</b>	$\text{mmol m}^{-3} \text{ year}^{-1}$	0.0785	$\pm 0.0022$
<b>Phosphate</b>	$\text{mmol m}^{-3} \text{ year}^{-1}$	0.0002	$\pm 6.2\text{e-}5$
<b>Chlorophyll</b>	$\text{mg m}^{-3} \text{ year}^{-1}$	0.0010	$\pm 0.0002$
<b>PPR</b>	$\text{mmol m}^{-3} \text{ d}^{-1} \text{ year}^{-1}$	0.0007	$\pm 0.0002$
<b>aD%O</b>	$[\%] \text{ year}^{-1}$	-0.0079	$\pm 0.0040$

**Table 3 Trend of simulated ecosystem variables**

All ecosystem variables do have a small but significant trend, however the trend of the surface nitrate concentration is by far the largest one (Table 3).

The temporal evolution of nitrate is presented in Figure 3, the increasing trend could be clearly seen. A more detailed statistical analysis of the nutrient trends including the identification of specific temporal variations using Singular Spectrum Analysis (SSA) can be found in Macias et al. (2014b).



**Figure 3 Temporal evolution of surface nitrate (R1\_RF\_RN)**

### 5.1.3 Frequency distributions of input variables

The density plots (area under the curve normalized to 1) show clearly that the monthly means of the selected variables do not follow any theoretical distribution (as normal, lognormal,...) but show a rather complicated behaviour. For comparison the corresponding curve for data following a theoretical normal distribution is added as broken red line. Therefore the above given mean values calculated under the assumption of an underlying normal distribution are only very approximate estimators of the true mean (expected value). Nitrate is the only variable showing a distribution somewhat similar to a normal distribution (Figure 3). Chlorophyll (Figure 5) and oxygen (Figure 6) distributions do have even 2 pronounced local maxima (bimodal distribution).

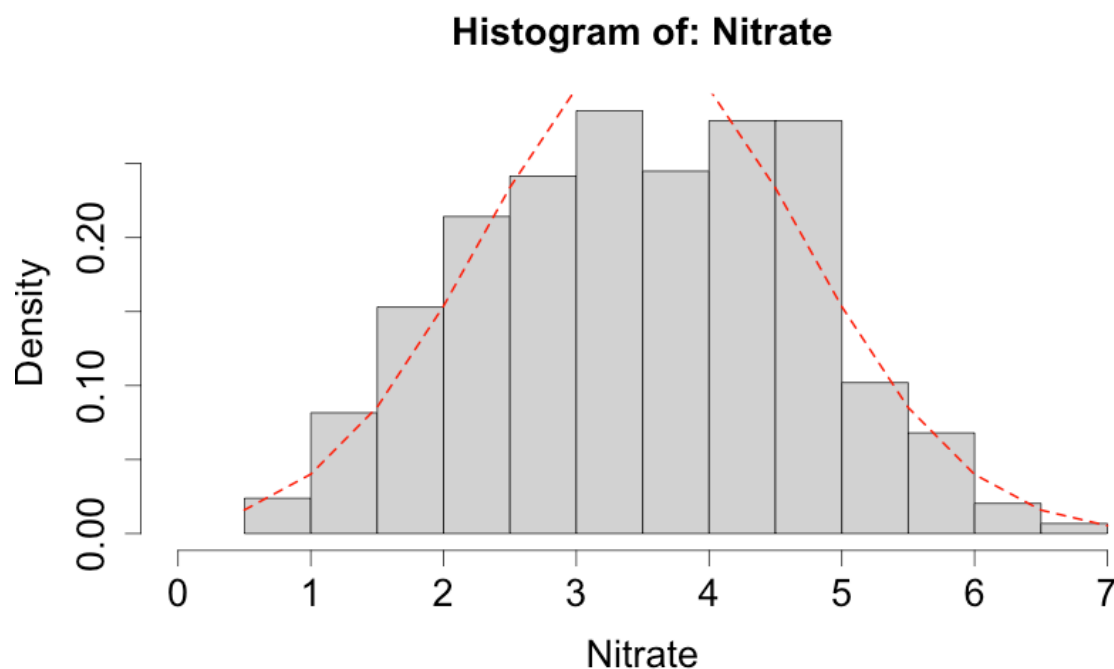


Figure 4 Histogram of nitrate concentrations [ $\text{mmol m}^{-3}$ ] (R1\_RF\_RN)

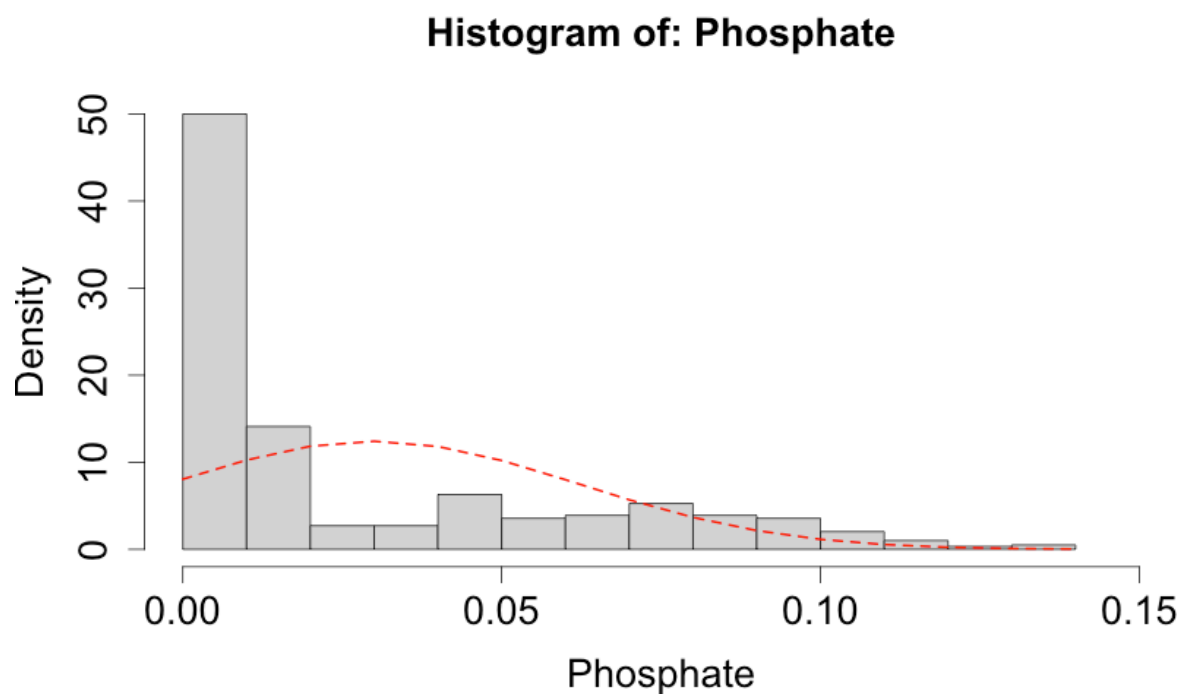


Figure 5 Histogram of phosphate concentrations [ $\text{mmol m}^{-3}$ ] (R1\_RF\_RN)

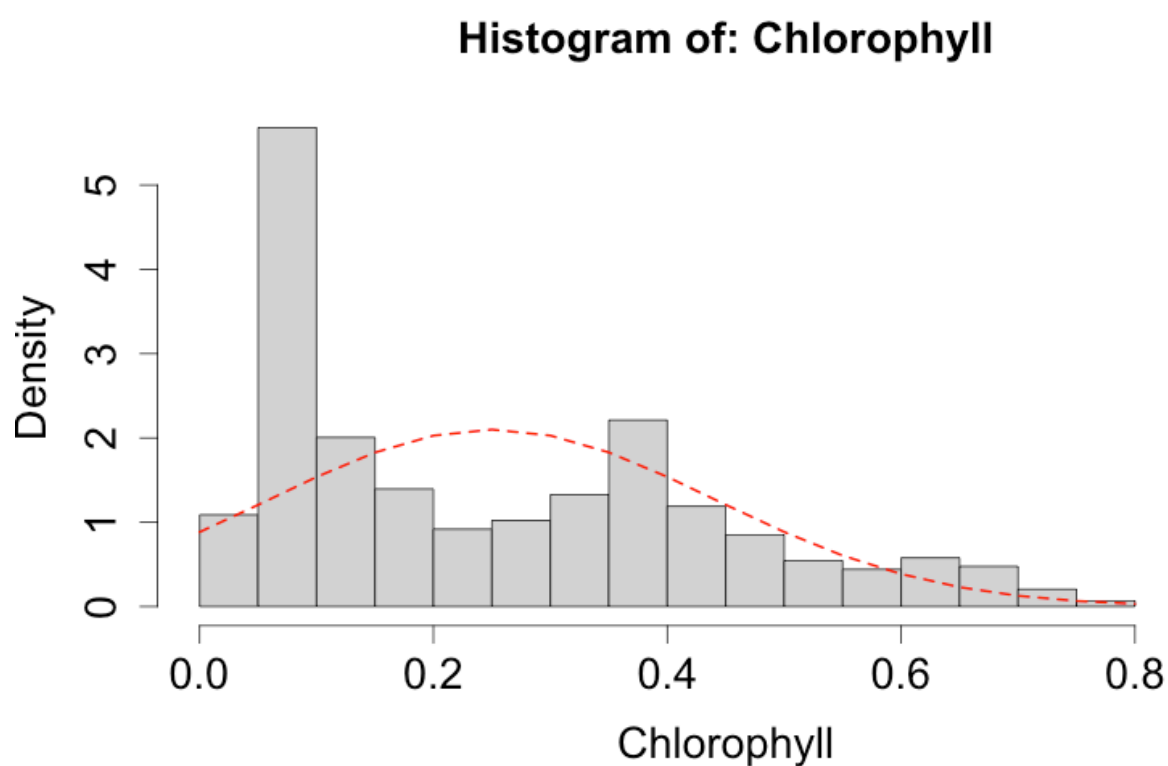
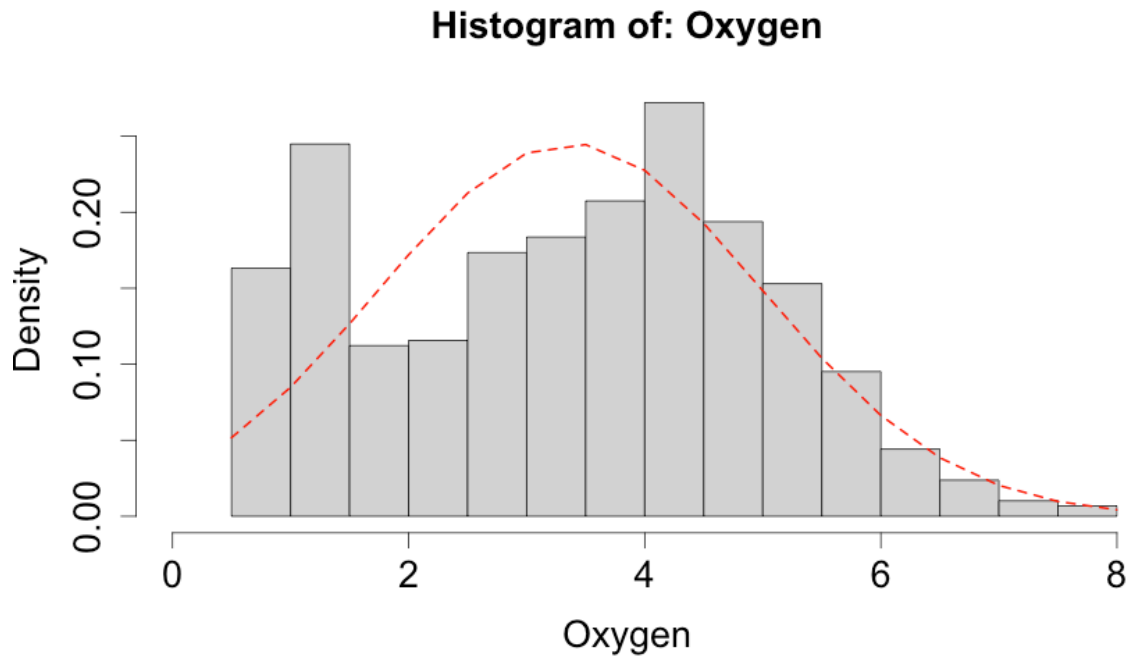


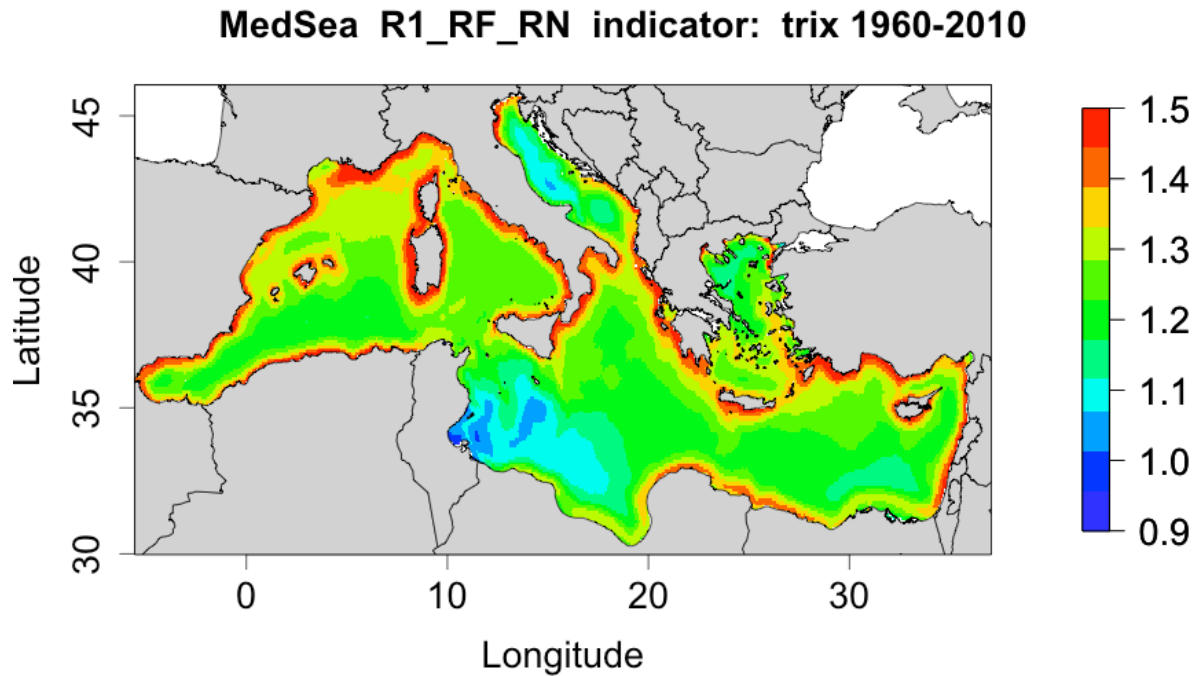
Figure 6 Histogram of chlorophyll concentrations [ $\text{mg m}^{-3}$ ] (R1\_RF\_RN)



**Figure 7 Histogram of oxygen concentrations [mmol m<sup>-3</sup>] (R1\_RF\_RN)**

## 5.2 Mean spatial TRIX distribution

First we apply the methodology of calculating the TRIX indicator to ecosystem data from the Mediterranean Sea (Macias et al. 2014a). In Figure 8 we see the indicated increasing eutrophication trend from lower values in the open sea to higher values at the coast, as well as several eutrophication hot spots in areas where large rivers are discharging. Despite that the general features seem to be quite reasonable, it is very likely that the eutrophication state in the Adriatic Sea and in the Gulf of Gabes (both identified by bluish colours in Figure 8) is underestimated due to model deficiencies (Macias et al. 2014).

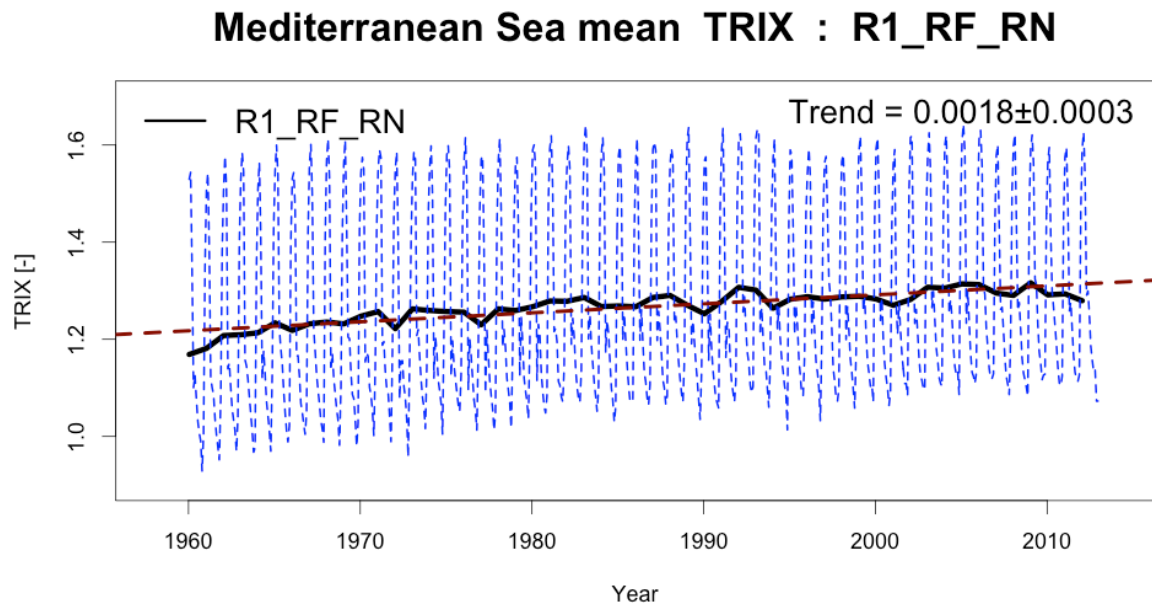


**Figure 8 Mediterranean Sea 50 years mean spatial eutrophication map, as captured by the TRIX indicator. The worsening spatial trend from the open sea towards the coast and especially critical situations near river mouths can be identified.**

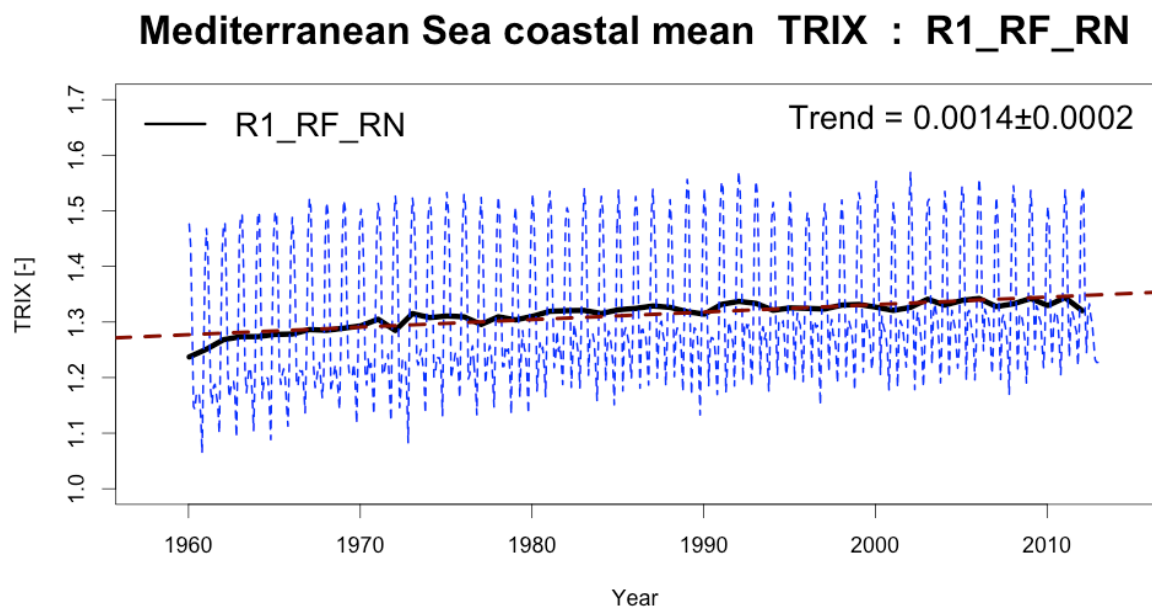
### 5.3 Temporal evolvement of TRIX index

The 50 years realistic hindcast simulation (reference run R1\_RF\_RN) allows for assessing the long term eutrophication trend in the Mediterranean Sea. The scaled annual mean TRIX values show a small but significant increasing trend of  $0.0018 \pm 0.0003$  over the last 5 decades, indicating a slight worsening of the overall Eutrophication State in the Mediterranean Sea (Figure 9). As we did see clear differences between the coastal areas (shallower than 100m) and the deeper parts (>100m) we investigate the trend in these two regions separate.

The trend in both regions is significant increasing, confirming the statement made above about worsening conditions. Interestingly the trend in the coastal region (Figure 10) is smaller than the trend in the deep sea (Figure 11). This seems to indicate that the overall worsening eutrophication trend is more caused by worsening conditions in the open sea areas of the Mediterranean Sea and less so by increasing coastal eutrophication.

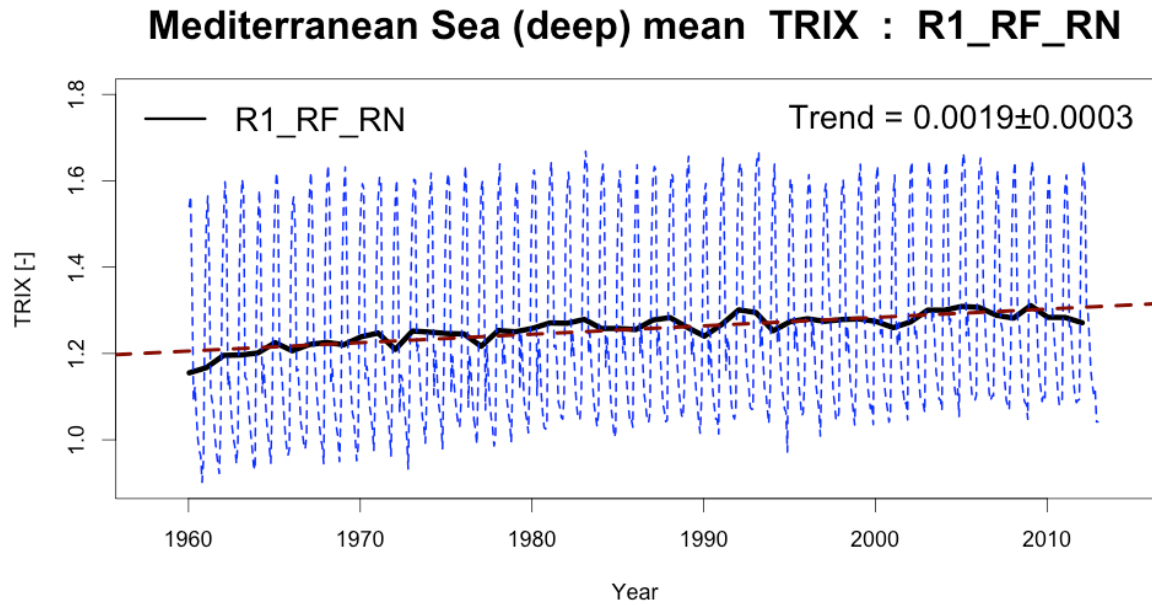


**Figure 9** Temporal evolvement of Mediterranean Sea TRIX (R1\_RF\_RN)



**Figure 10** Temporal evolvement of Mediterranean coastal TRIX (R1\_RF\_RN)





**Figure 11 Temporal evolution of Mediterranean deep sea TRIX (R1\_RF\_RN)**

## **5.4 Temporal evolution of Mediterranean Eutrophication Ratio**

Here we follow the procedure developed by HELCOM for calculating the HEAT Eutrophication Ratio (ER) with minor modifications and apply it to the ecosystem variables of the Mediterranean Sea. The increasing trend of the TRIX indicator is confirmed (even substantially stronger) by the ER indicator trend (Figure 12). We remind that the scaling should be only considered as relative; especially as no agreed target values exist for the Mediterranean Sea. This example calculation however supports the idea that indicators developed for a specific region could be successfully applied on very different regional seas.

### Eutrophication ratios HEAT3 Mediterranean Sea (ERGOM)

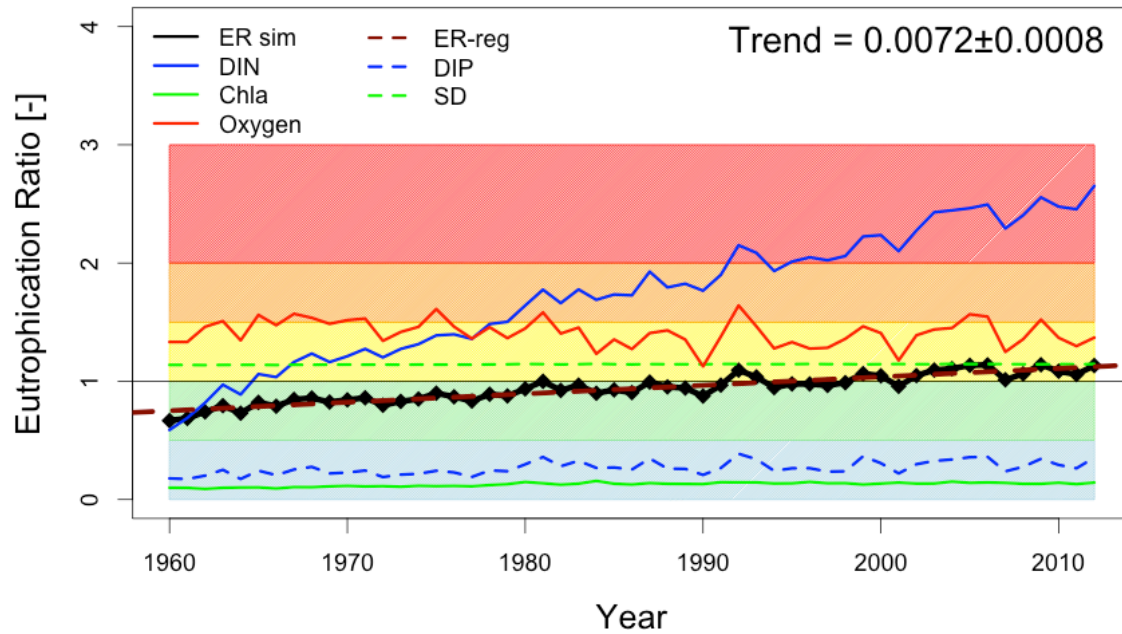


Figure 12 Mediterranean Sea HEAT (ER) indicator (R1\_RF\_RN)

## 5.5 Potential reasons for increasing eutrophication state

Both examined indicators TRIX and HEAT (ER) clearly showed increasing (worsening) eutrophication trends for the overall Mediterranean Sea. We are here briefly investigating the likely causes for the increasing TRIX and HEAT values in the Mediterranean Sea. Indeed as could be seen from Figure 12 only the nitrate eutrophication ratio is increasing strongly. This is confirmed by the calculated linear trends (Table 4), giving a nitrate ER trend of about 1 order of magnitude larger than the other trends. Therefore it is quite likely that the increasing surface nitrate concentrations are responsible for the increasing eutrophication trend in the Mediterranean Sea. Trends of chlorophyll, Secchi Depth (proxy) and oxygen concentration are basically non existent.

<b>Variable</b>	<b>Trend</b>	<b>Range</b>
<b>HEAT_ER</b>	0.0072	±0.0008
<b>DIN_ER</b>	0.0345	± 0.0017
<b>DIP_ER</b>	0.0022	± 0.0008
<b>CHL_ER</b>	0.0009	±0.0002
<b>SD_ER</b>	0.0002	±3.0e-5
<b>OXY_ER</b>	No	No

**Table 4 Trend of the eutrophication ratio ER components Mediterranean Sea.**

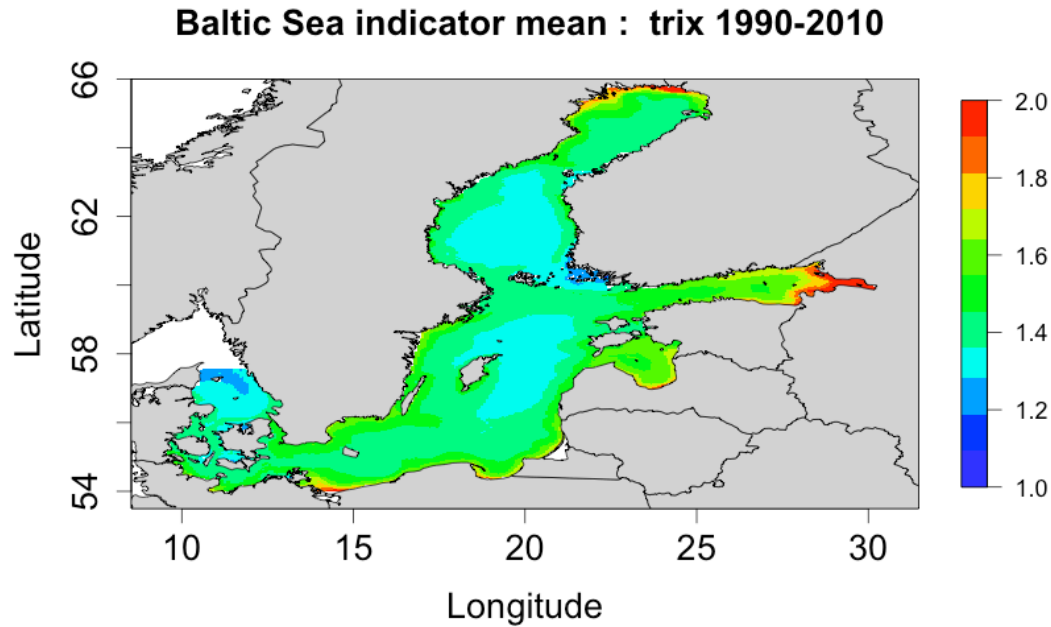
## 6. Comparative assessment of TRIX and HEAT - Baltic Sea

Here we apply the described method to calculate the TRIX and HEAT indicators using ecosystem model data from a realistic 20 years simulation of the Baltic Sea (Lessin et al. 2014). The application to the Baltic Sea allows the comparison with assessments made by other groups and HELCOM.

### 6.1 Baltic Sea spatial TRIX

Using the data from the above described ecosystem simulation of the Baltic Sea for the period from 1990 to 2010 for calculating the temporal mean TRIX index we again find several clear indicated hotspot areas (Figure 13). Highest values are found in the Gulf of Finland (near the mouth of river Neva), in the very north of the Bothnian Bay, the Gulf of Riga and near to the mouth of river Odra (Pomeranian Bay). Further we find again a clear-evidenced trend of increasing TRIX values from the open sea in direction to the coasts and especially high values in the vicinity of rivers. Considering these regional differences it is clear that the Baltic Sea overall mean value might not be representative of the actual eutrophication status, because of the applied averaging procedure.

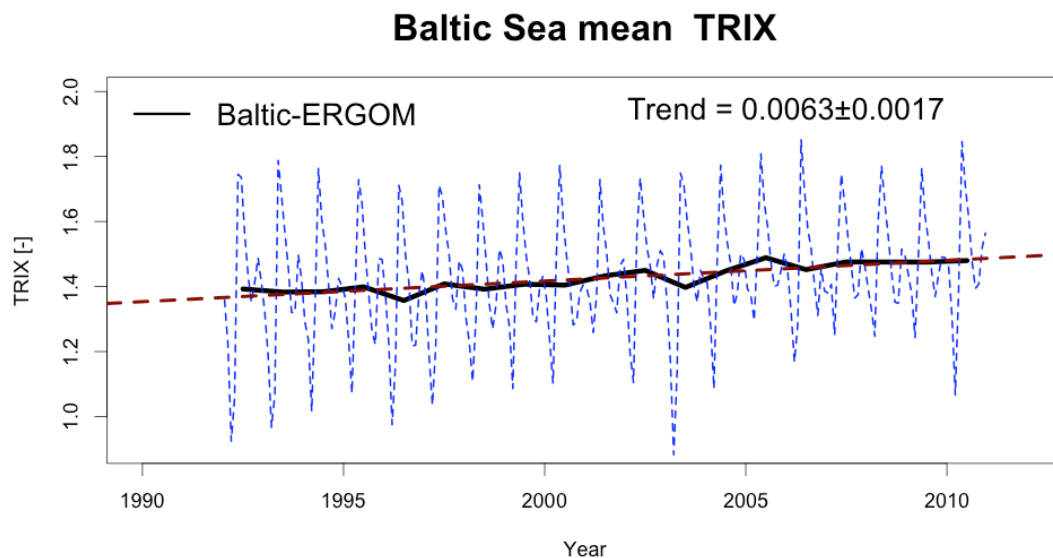
Despite that the here calculated TRIX values do not represent an absolute scale of the ES we could note the different scale compared to Figure 8. The calculated TRIX values in the Mediterranean Sea are smaller than in the Baltic Sea, which may be indicating a less severe eutrophication problem in the Mediterranean Sea. It is however difficult to compare the spatial explicit results based on high resolution model data to the rather coarse eutrophication assessment as provided by HELCOM (<http://helcom.fi/baltic-sea-trends/eutrophication/latest-status>). The latest HELCOM assessment describes most of the Baltic as affected by eutrophication and does therefore not allow identifying spatial trends. In the HELCOM assessment ER values of 1 and smaller would indicate GES (the smaller the better). We adjusted the here applied relative TRIX scaling in such a way that values smaller than 1 would correspond roughly to qualify the region as being in GES (smaller is better). In general therefore the assessment based on the TRIX indicator agrees with the HELCOM assessment, that most of the Baltic Sea region is affected by eutrophication. Unfortunately it is not really possible to compare the spatial trends between these two assessments.



**Figure 13** Baltic Sea 20 years mean spatial eutrophication map, as captured by the TRIX indicator. The worsening spatial trend from the open sea towards the coast and especially critical situations near river mouths can be identified.

## 6.2 Baltic Sea temporal TRIX evolution

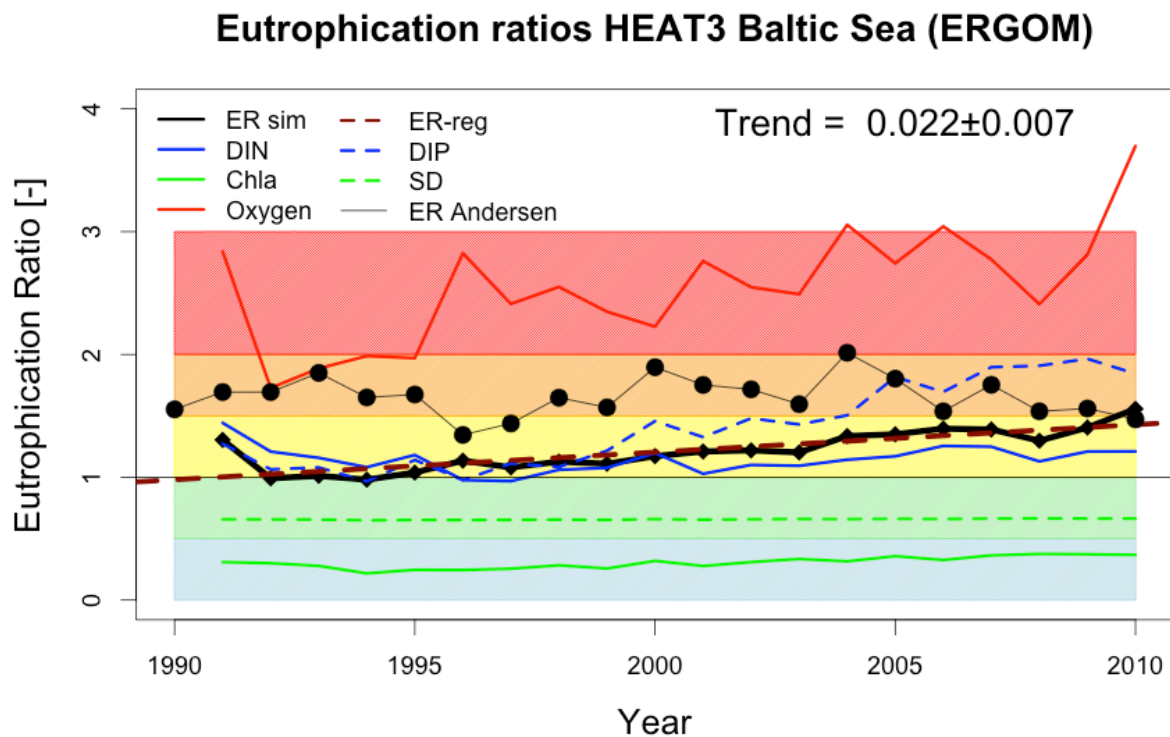
The 20 years realistic hindcast simulation allows for assessing the medium term eutrophication trend in the Baltic Sea. The scaled annual mean TRIX values show a small but significant increasing trend of  $0.0063 \pm 0.0017$  over the last 2 decades (Figure 14), indicating a slight worsening of the overall Eutrophication State in the Baltic Sea. The trend in the Baltic Sea is significant larger than in the Mediterranean Sea. In case of the monthly calculated TRIX values the large annual cycle is noteworthy (Figure 14).



**Figure 14** Temporal evolution of Baltic Sea TRIX indicator

### 6.3 Baltic Sea HEAT

Andersen et al. (2015) investigated the long-term temporal and spatial trends in the eutrophication status of the Baltic Sea. They concluded that recent improvements in the eutrophication status could be seen and had led to large-scale alleviation of eutrophication and a healthier Baltic Sea. However Fleming-Lehtinen et al. (2015) concluded that from their assessment the entire open Baltic Sea was affected by eutrophication, indicating a worsening trend. It will be interesting to see our results in view of these each other contradicting opinions. We apply the basic methodology used in HEAT, with some simplifications, to data derived from carefully calibrated and validated ecosystem model simulations (Lessin et al. 2014). Figure 15 displays the calculated Eutrophication Ratio (ER-sim black line), values below 1.0 could indicate a good environmental status. Based on measured data Andersen et al. (2015) calculated ER values around 1.7 for the period from 1990 to 2010; see the large black dots in **Error! Reference source not found..** They pointed to a decreasing ER trend during this period. However, using their ER data covering only the period from 1990 to 2010 we do not find any significant trend. Our annual spatial mean values, based on gridded data of the full Baltic Sea are smaller (around 1.3), likely because of the large averaging effect from the spatial explicit grid. Our calculated mean ER shows a small but significant increasing trend ( $0.022 \pm 0.007$ ), pointing to worsening conditions. Therefore our assessment seems to be more in agreement with the conclusions from Fleming-Lehtinen et al. (2015).



**Figure 15 Temporal evolvement of Baltic Sea HEAT (ER) indicator**

## 6.4 Potential reasons for the increasing eutrophication state

Both examined indicators TRIX and HEAT (ER) clearly showed increasing (worsening) eutrophication trends for the overall Baltic Sea. Therefore we are here briefly investigating the likely causes for the increasing TRIX and HEAT values in the Baltic Sea. Indeed as could be seen from Figure 15 only the phosphate eutrophication ratio and may be oxygen ER seem to increase. This is confirmed by the calculated linear trends (Table 5), giving a phosphate and oxygen ER trend of about 1 order of magnitude larger than the other trends. Therefore it is quite likely that the increasing surface phosphate concentrations are mainly responsible for the increasing eutrophication trend in the Baltic Sea. The similar strong increasing trend in the oxygen ER indicator might be partially influenced by the reduced inflow activity from the North Sea during this period. Trends of chlorophyll, Secchi Depth (proxy) and nitrate concentration are basically non-existent.

Variable	Trend	Range
HEAT_ER	0.02241	$\pm 0.0075$
DIP_ER	0.05221	$\pm 0.0117$
OXY_ER	0.05209	$\pm 0.0293$
CHL_ER	0.00632	$\pm 0.0025$
SD_ER	0.00057	$\pm 0.0002$
DIN_ER	No	No

**Table 5 Trend of the eutrophication ratio components Baltic Sea**

## 7. Eutrophication scenarios Mediterranean Sea

An attempt has been made to provide scenario simulations focusing on two main aspects, namely climate variability and nutrient's input. The baseline run (described above) uses realistic atmospheric forcing and realistic nutrient input from rivers (R1\_RF\_RN).

We constructed a climatological atmospheric forcing by averaging 50 years of meteorological data, in order to investigate the impact from reduced climate variability. The second simulation was, thus forced by this artificial surface heat, salt and momentum fluxes acting on the water body (R2\_CF\_RN). River nutrients were kept realistic in this case. In the third scenario simulation additionally the nutrient input from the rivers around the Mediterranean Sea was reduced (R3\_CF\_NO). This scenario serves to assess in a very simplified way the potential effectiveness of nutrient reduction measures. We focus here only on relative changes caused by the effect from the applied forcing change compared to the baseline run, in order to eliminate as far as possible absolute model errors. An overview about the performed scenarios is given in Table 6.

Run (long)	Short	Forcing	River Nutrients	Period
R1_RF_RN	R1	ERA40/ERA-Interim	Realistic	1960-2012
R2_CF_RN	R2	CLIMATE	Realistic	1960-2011
R3_CF_NO	R3	CLIMATE	None	1960-2008

Table 6 Selected scenarios

### 7.1 Brief description of the scenarios

All model runs have been made with the exact same configuration, as described above, only atmospheric forcing and nutrient loads in rivers have been changed between the different scenarios.

#### 7.1.1 Realistic hindcast (R1\_RF\_RN)

This baseline run uses the exact same external forcings (atmosphere and nutrients from rivers) as described in Macias et al. (2014b). This model run for the Mediterranean Sea is forced at surface every 6 hours with ECMWF reanalysis products. Specifically, we use the ECMWF ERA40 reanalysis products from 1957 to 1978 and the ERA-Interim products from 1979 to 2011 (available from <http://www.ecmwf.int>). The consistency of these data sets has been checked to avoid spurious results. Nutrient content (nitrate and phosphate) of freshwater runoff were obtained from Ludwig et al. (2009). In case of missing data, climatological values were used.



### 7.1.2 Influence from reduced forcing variability (R2\_CF\_RN)

For the first scenario, rivers conditions (freshwater flow and nutrient loads) were kept the same as for the baseline run. However, atmospheric forcing was changed to a climatological year. This was done by averaging all atmospheric variables for each day of the year during the considered period (1960 ~ 2010). This way the seasonal cycle is retained but no interannual variability is included. The ocean model is then forced by applying the same climatological atmospheric conditions for 50 consecutive years.

### 7.1.3 No river nutrient input scenario (R3\_CF\_NO)

The second scenario uses the same climatological forcing as described above (R2\_CF\_RN), but assumes zero nutrient inputs from all freshwater sources. All nutrients' concentrations in the 39 rivers are considered null for the entire duration of the run (50 years). The nutrient input from the Dardanelles was also set to zero.

## 7.2 Impact from reduced forcing variability

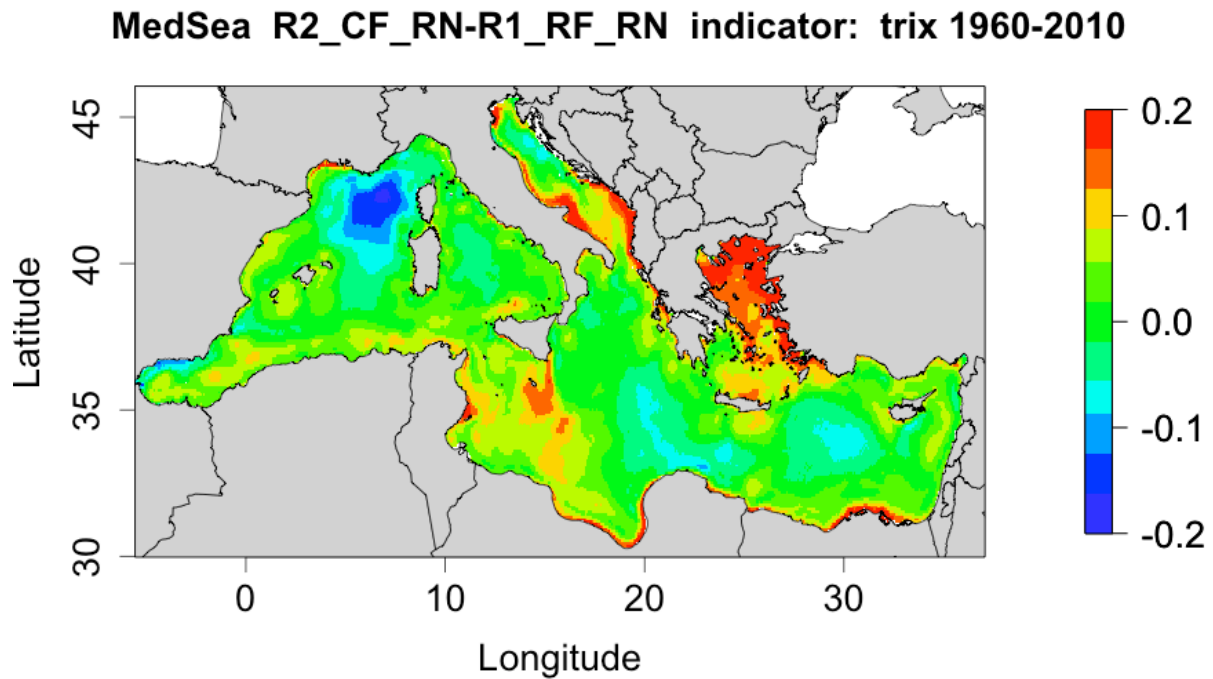
First we compare the spatial difference of the temporal mean between the realistic simulation (baseline) R1\_RF\_RN and the simulation that is using climatological forcing R2\_CF\_RN (no interannual variability). When using climatological forcing data the mean of the meteorological variables is not changed in a significant way, but the variability of the wind speed is drastically reduced, see Table 7.

This will consequently reduce all types of physical mixing comprising surface mixing, deep water convection, turbulent vertical diffusion and upwelling.

Variable	Statistics	R1_RF_RN	R2_CF_RN	Difference	Diff [%]
<b>Temperature T2</b>	Mean	19.818	19.842	-0.024	0.121
[degree Celsius]	Stdev	4.860	4.758	0.1019	2.098
<b>Dewpoint D2</b>	Mean	14.060	14.059	0.0016	0.011
[degree Celsius]	Stdev	4.890	4.6634	0.2269	4.640
<b>Wind U10</b>	Mean	1.3868	1.3887	-0.0019	0.137
[m s <sup>-1</sup> ]	Stdev	2.3665	0.5549	1.8116	76.55
<b>Wind V10</b>	Mean	-1.0882	-1.0981	0.0099	0.909
[m s <sup>-1</sup> ]	Stdev	1.6548	0.5244	1.1304	68.31
<b>Pressure SLP</b>	Mean	101533	101531.4	1.6	0.001
[Pascal]	Stdev	456.8	184.5	272.3	59.6

Table 7 Statistics of meteorological data

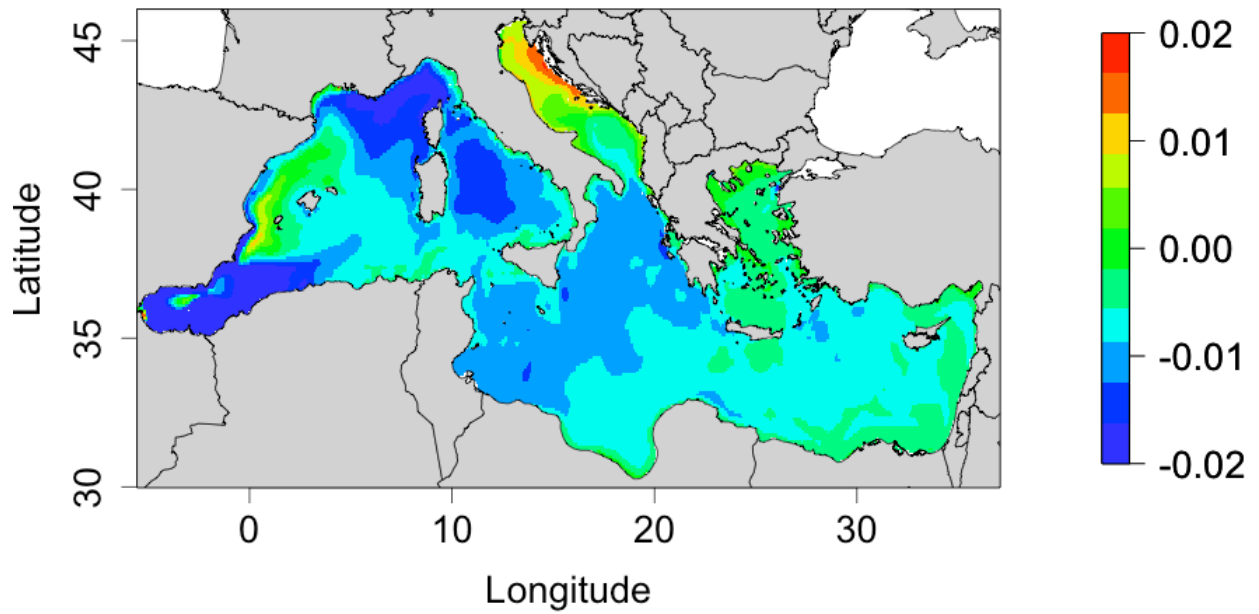
In Figure 16 we see that especially coastal regions would suffer from such a reduced wind forcing activity (see red colours in the Aegean Sea, Adriatic Sea and the vicinity of Po, Nile, Rhone mouth). Only the deep upwelling region near to the Gulf of Lion, in the northwestern Mediterranean Sea would improve, likely due to reduced deep winter convection that would supply less nutrients to the surface.



**Figure 16 Difference in TRIX between R2 and R1**

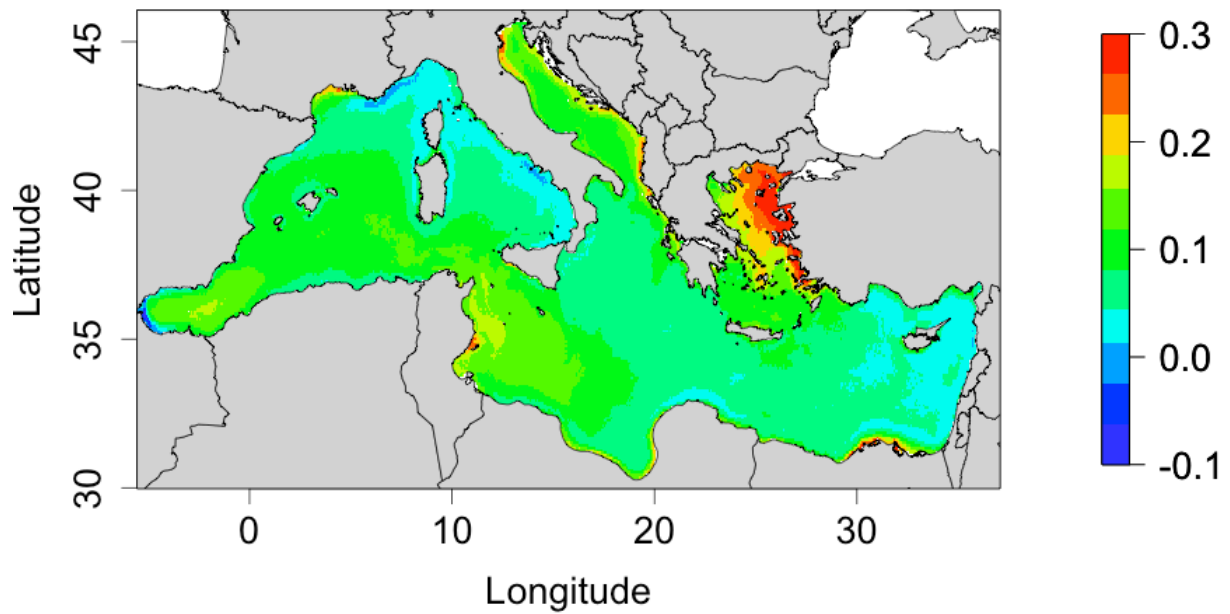
Looking in more detail for the reasons of these changes, we find that nitrate is slightly worsening (increasing) only in the Adriatic Sea (Figure 17). Most other parts but especially the Gulf of Lion is however slightly improving, there may be caused by reduced deep convection. As the Alboran Sea is very near to the model boundary we will not discuss potential improvements there. This behaviour of nitrate does not explain the TRIX changes in the Aegean Sea. Interestingly the main reasons for the worsening conditions (TRIX) in the Aegean Sea are the worsening oxygen conditions there, Figure 18. Actually, oxygen conditions seem to worsen in most parts of the Mediterranean Sea Figure 18.

**MedSea R2\_CF\_RN-R1\_RF\_RN indicator: n\_ind 1960-2010**



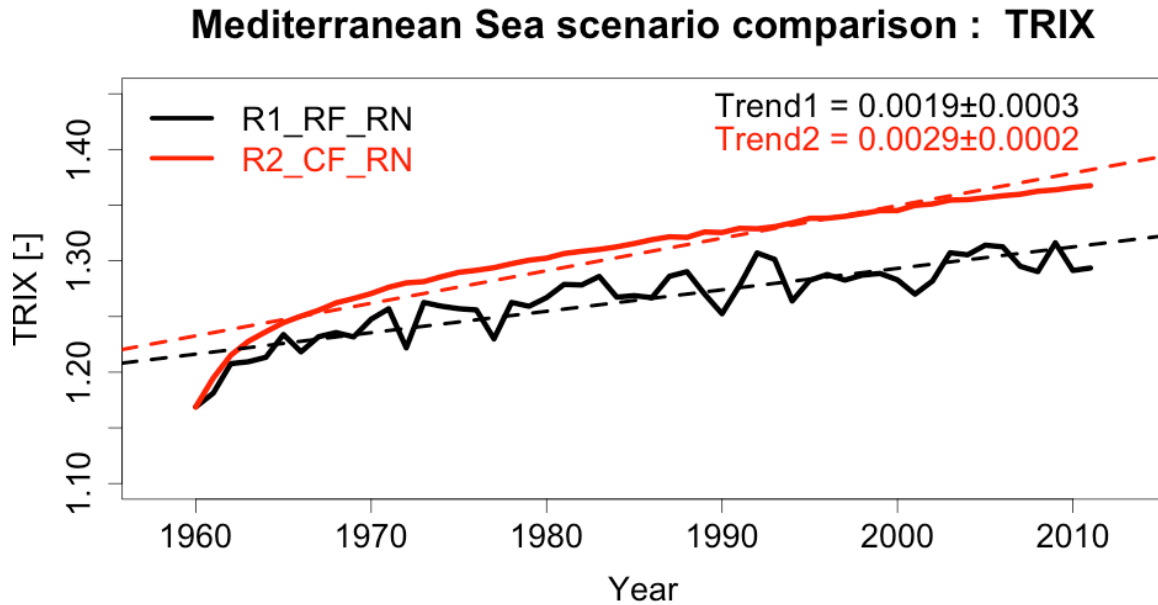
**Figure 17** Difference nitrate indicator between R2 and R1

**MedSea R2\_CF\_RN-R1\_RF\_RN indicator: o\_ind 1960-2010**



**Figure 18** Difference oxygen indicator between R2 and R1

The mean temporal evolution of these 2 simulations (Figure 19) evidences the negative global impact from reduced climate variability on the eutrophication state. The simulation R2\_CF\_RN shows soon after the beginning of the run clearly larger (worse) TRIX values and has a significant stronger increasing trend.



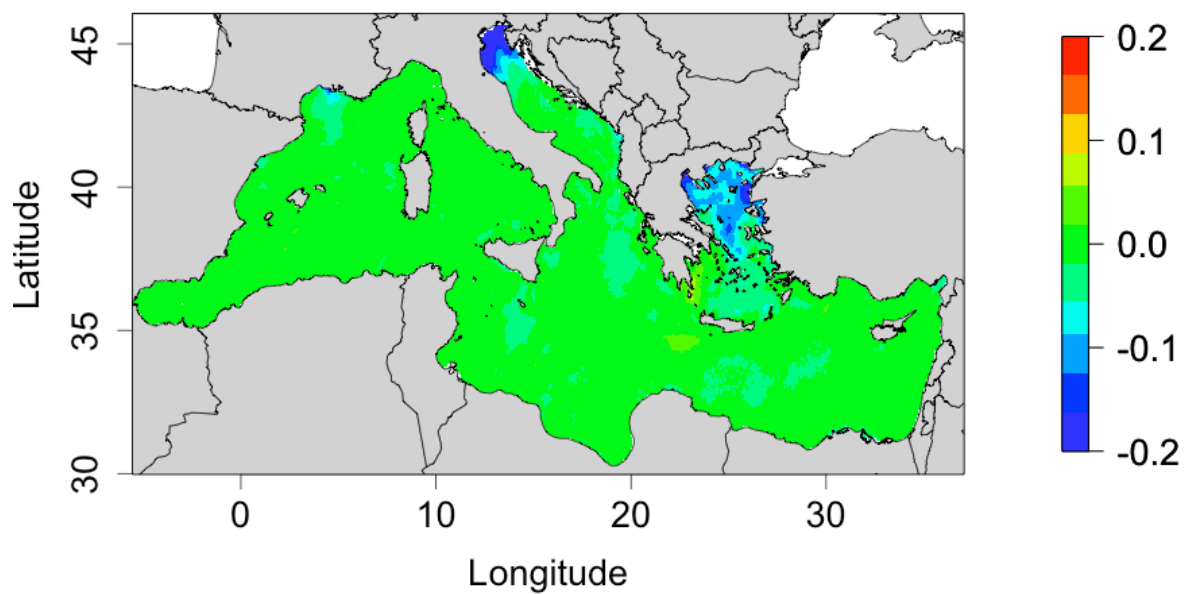
**Figure 19 Temporal evolution of R1\_RF\_RN and R2\_CF\_RN**

### 7.3 Impact from reduced river nutrient input

By comparing scenarios R2 and R3 the direct impact of the rivers' nutrients inputs on the eutrophication status of the Mediterranean Sea under climatological atmospheric forcing could be assessed. The difference between the TRIX indicator between these simulations is shown in Figure 20, blue colours point to an improvement (reduced eutrophication). We find an especially strong improvement in the Adriatic Sea and some smaller improvement in the Aegean Sea and in the Gulf of Lion. Surprisingly the complete elimination of all external nutrient inputs seems to result in a rather limited overall improvement.

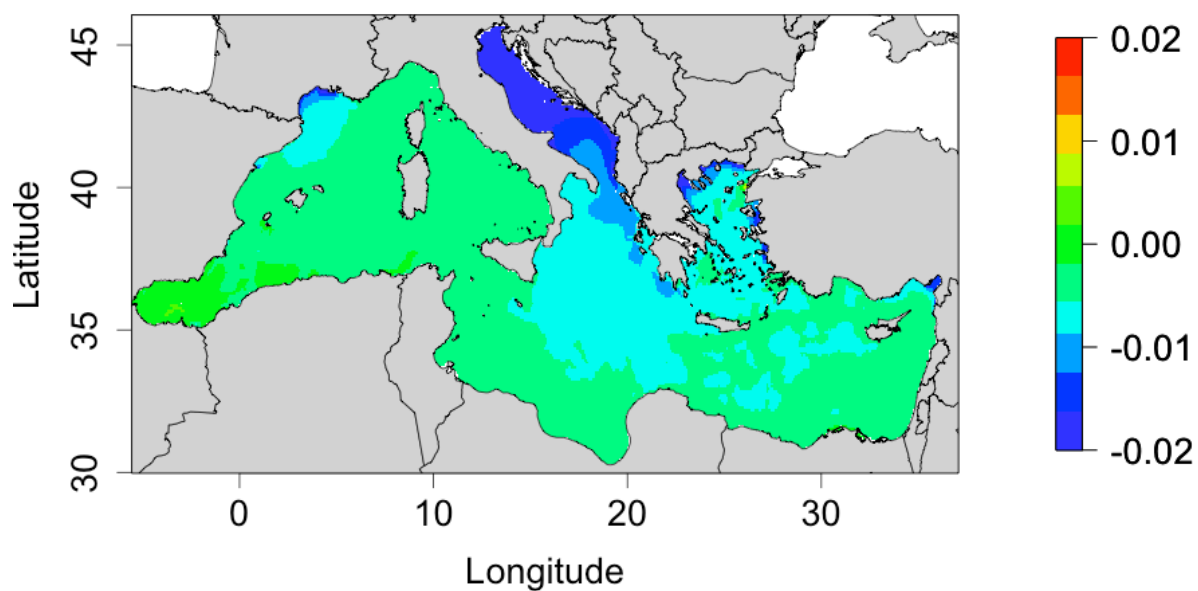
Searching for the responsible causes of reduced TRIX values in the different regions, we find that the improvement in the Adriatic Sea is caused by reduced surface nitrate concentrations and therefore is likely a direct consequence of the reduced nitrate input (Figure 21). For nitrate we do however see only a small improvement in the Aegean Sea and the Gulf of Lion. Looking at Figure 22 we find that very likely the change in the Aegean Sea is at least partly due to improved oxygen conditions and is therefore an indirect consequence of the reduced nutrient input. In summary we find improvements in response to the reduced nutrient input, but they are rather spatially confined to regions influenced by river water supply. The improvement in the Aegean Sea is likely caused by the nutrient reduction in the inflowing water from the Black Sea.

**MedSea R3\_CF\_NO-R2\_CF\_RN indicator: trix 1960-2010**



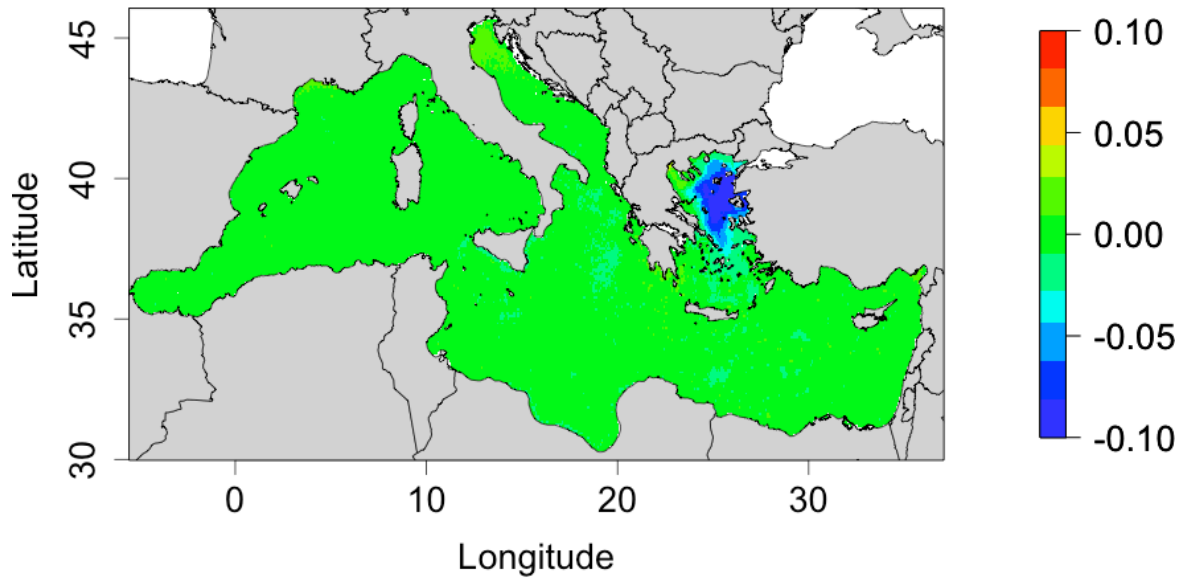
**Figure 20 Difference TRIX indicator between R3 and R2**

**MedSea R3\_CF\_NO-R2\_CF\_RN indicator: n\_ind 1960-2010**



**Figure 21 Difference nitrate indicator between R3 and R2**

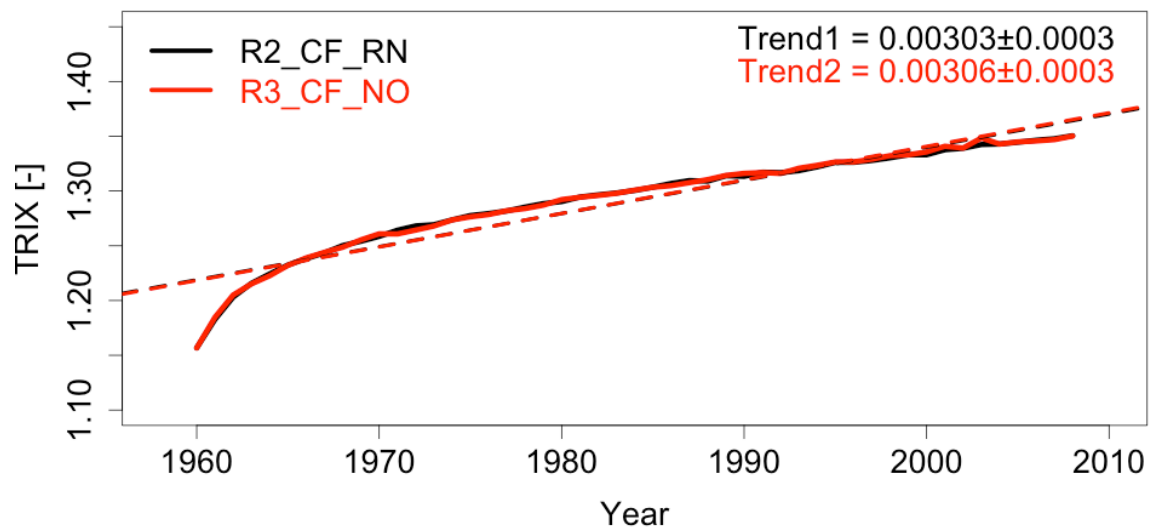
### MedSea R3\_CF\_NO-R2\_CF\_RN indicator: o\_ind 1960-2010



**Figure 22 Difference oxygen indicator between R3 and R2**

Spatially averaging the full Mediterranean Sea gives the surprising result that the overall mean TRIX values, as well as the temporal trend are not significant different between the simulations with and without river nutrient input (Figure 23).

### Mediterranean Sea scenario comparison : TRIX



**Figure 23 Temporal evolvement of TRIX indicator (R2 and R3)**

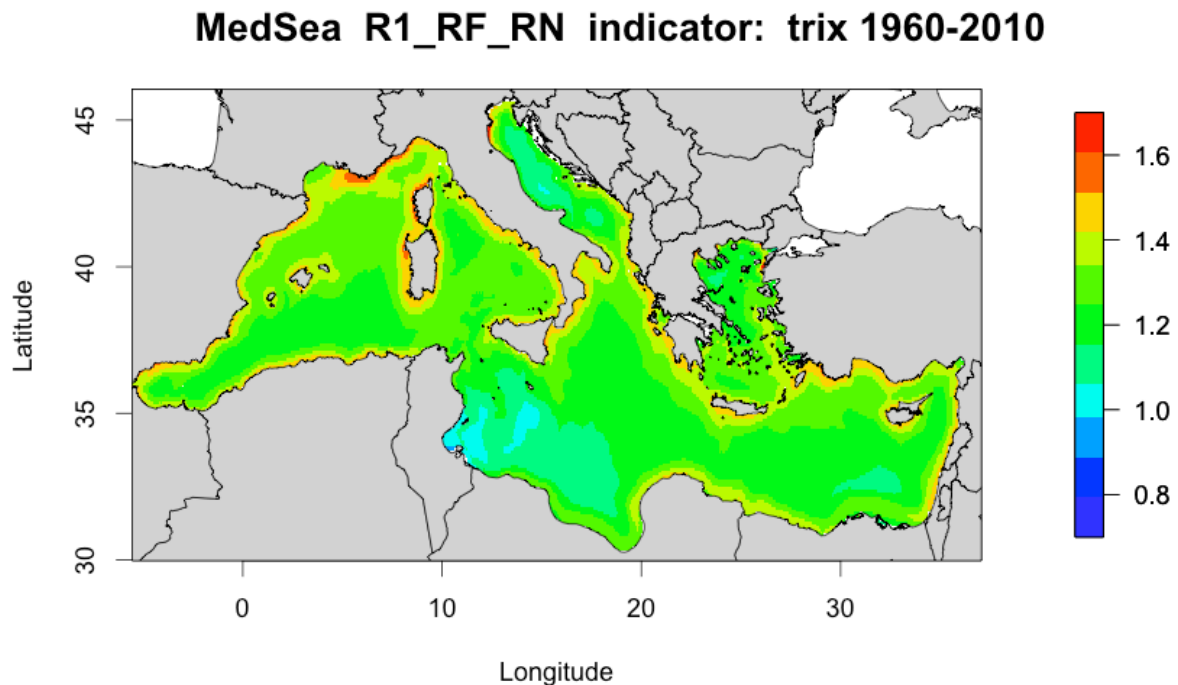
## 8. A potential methodological improvement

As discussed already by Vollenweider et al. 1998, the usage of chlorophyll as an indicator for primary production is only a rather crude substitution. Indeed accepting the eutrophication definition in the sense of “increased production” it is clear that instead of the proxy chlorophyll the primary production rate (PPR) should be used. The choice of chlorophyll is likely due to the general much better availability and reliability of chlorophyll data compared to PPR data from in situ measurements.

This is however very different for simulated data, as indeed in ecosystem models primary production rates are routinely calculated and could therefore be used to calculate corresponding eutrophication indicators.

Here we present one example for calculating the TRIX indicators by using PPR instead of chlorophyll (named now *rtrix*). Both indicators are shown on same scale in Figure 24 and Figure 25. The (non calibrated) difference plot between them in Figure 26 highlights the major differences. Higher values of the difference *rtrix*-*trix* (red colours) indicate that according to *r*TRIX the eutrophication situation in the Adriatic Sea, Gulf of Thermaikos and in the southern Ionian Sea would be much worse compared to the assessment based on the TRIX calculation. On the other hand a much better eutrophication state would be indicated for several coastal zones, especially the African coasts (blue colours Figure 26).

This evaluation based on PPR might reflect the real eutrophication state better than the original TRIX based on chlorophyll. This variable replacement could be also easily applied to the HEAT indicator. However a more detailed investigation, especially a comparison with measured data is still lacking.



**Figure 24 TRIX indicator**

### MedSea R1\_RF\_RN indicator: rtrix 1960-2010

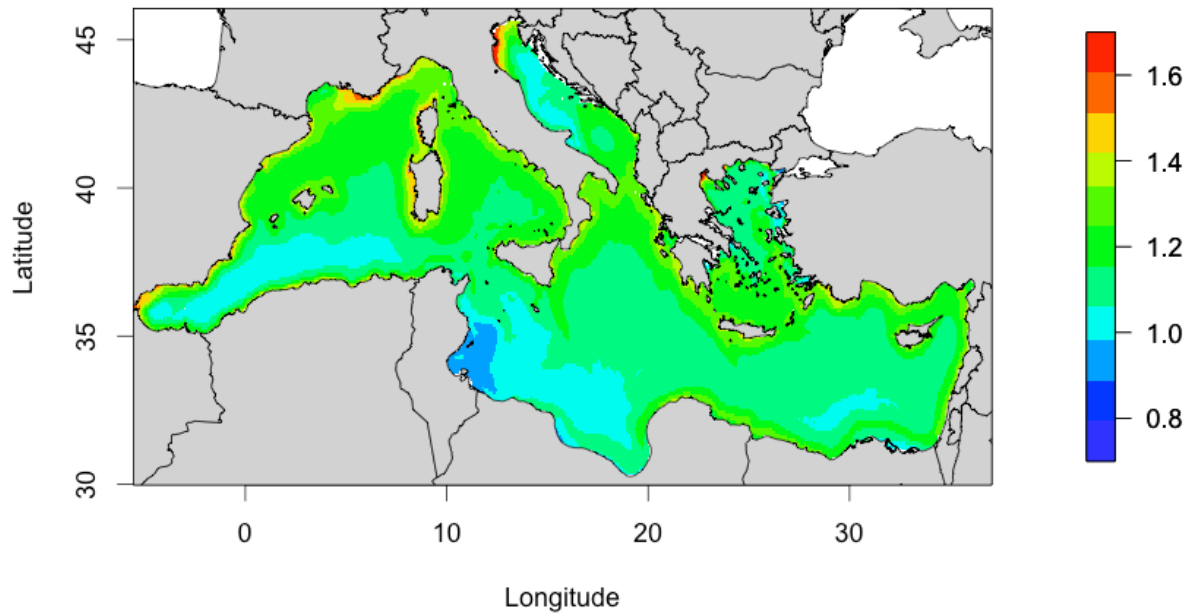


Figure 25 rTRIX indicator, based on PPR instead of Chla

### MedSea R1\_RF\_RN : rtrix-trix (1960-2010)

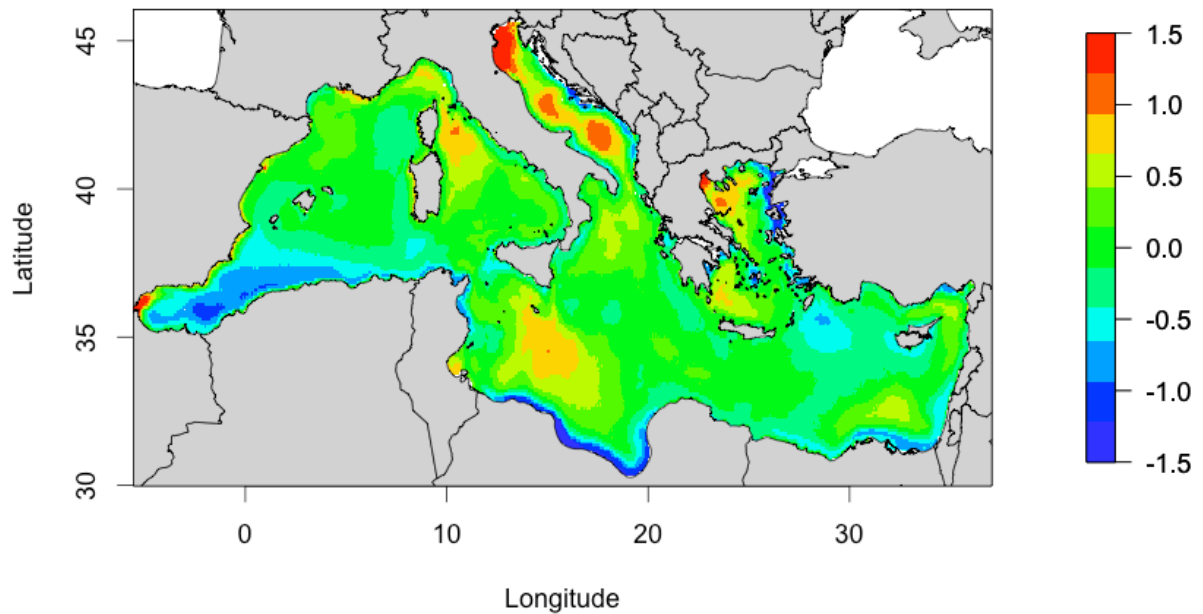


Figure 26 Difference between rTRIX and TRIX



## 9. Summary

Based on ecosystem simulations provided by well calibrated and validated models we calculated representative eutrophication indicators for the Mediterranean and the Baltic Sea.

We are here focusing on demonstrating the usefulness of ecosystem model data for assessing eutrophication aspects, as covered by MSFD descriptor D5. The assessments are based on calculating indicators, namely the already long ago established trophic indicator TRIX and for comparison the more recent HEAT indicator (as applied by HELCOM). Both these indicators are based on the same basic underlying principles and comprising eutrophication causes as well as direct and indirect effects.

We show that the use of ecosystem model data allows identifying sensitive areas and assessing long term trends in the development of eutrophication in 2 major European water bodies. The spatial explicit simulations allow the identification of eutrophication gradients and hot spots. Specifically strong spatial gradients from the open sea to the coast are detected in many variables and indicators. Figure 8 clearly shows that eutrophication is mainly a coastal problem, with high values near to the coast and low values in the open sea, when applying a consistent scaling.

The investigation of long term trends points to slightly increasing eutrophication problems in the Mediterranean Sea and the Baltic Sea. The overall temporal eutrophication trend in the Mediterranean Sea is towards worsening conditions (increasing indicators). This seems here to be mainly caused by increasing nitrate concentrations in the surface waters. However, in the Baltic Sea the increase in TRIX and HEAT indicators seems to be rather due to increasing phosphate concentrations.

In summary both TRIX and HEAT provide a rather consistent picture about the eutrophication state and trend. The assessment based on model data is basically consistent with the assessment based on measured data as performed by HELCOM.

We performed scenario simulations for investigating the impact from changing climate variability and from reducing nutrient inputs. Reduced climate variability (by using climatological atmospheric forcing) would lead to increasing eutrophication problems in many coastal regions and especially in the Aegean Sea. A possible minor improvement could be found in the deep convection area near to the Gulf of Lyon. The proposed nutrient reduction scenario achieves surprisingly minor overall improvements, which are clearly identifiable only in the Adriatic Sea and the Aegean Sea, regions actually suffering most from pronounced nutrient inputs.

Finally we demonstrated that the replacement of the chlorophyll indicator by a primary productivity indicator might help to achieve more reliable assessments, which are based on the real productivity of the considered system.

The quality of the ecosystem simulations is of critical relevance to the success of this approach and future model improvements will certainly provide more confidence in the results. The presented spatial and temporal eutrophication trends are the result of a first feasibility study, presenting the general approach and are therefore by no means the final word on eutrophication trends, but are thought to contribute to the assessment discussion.

## 10. Conclusion

The Marine Strategy Framework Directive (MSFD) aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020, and to protect the marine resources upon which economic and social activities depend.

The progress in marine modelling achieved during the last 30 years gives the possibility of more realistic simulations of many aspects of the marine environment. Therefore, now the use of marine modelling can support the assessment process of the marine environment as foreseen in the MSFD by defining baselines, addressing data gaps and allowing for scenario simulations.

During the last 5 decades the increasing nutrient inputs to marine and fresh water ecosystems, driven by extensive fertilizer use in agriculture, production of manure from animals, domestic sewage and atmospheric nutrient deposition resulting from fossil fuel combustion led to the global spread of marine eutrophication. Due to the obvious negative effects on marine and coastal ecosystems beginning in the 1980s first initiatives on nutrient input reduction measures were undertaken. It was expected that reduced nutrient inputs would reverse eutrophication effects and affected ecosystems could return to an earlier more oligotrophic state, an expectation that could be tested by performing dedicated scenario simulations.

Preliminary examples of applying the HEAT and the TRIX methodology to model data generated by the GETM/GOTM/FABM/ERGOM modelling environment to two ecological very different regions, the Baltic Sea and the Mediterranean Sea, are provided. These examples demonstrate their potential by clearly detecting the strong eutrophication gradient that is increasing from the open sea to the coast and pointing to certain eutrophication hot spots, as well as giving quantitative temporal trends. The identified small but significant temporal trend in both regional seas was found to be towards increasing eutrophication.

Both TRIX and HEAT provide a rather consistent picture about the eutrophication state and trend and they are not significantly different from each other. Further, they are in general agreement with conclusions from recent assessments based on measured data for the overall Baltic Sea. As measured data often do have large gaps in space and time, data from carefully validated ecosystem simulations provide the possibility to perform additional eutrophication assessments. Because of the better temporal and spatial coverage this approach could help to identify sensitive regions and critical time periods. It could also support the identification of trends and to detect relevant data gaps in the monitoring.

Contrary to the real world computer models provide the possibility to perform scenario simulations, which could allow answering "what if" questions.

The strength of this approach is the possibility to create and investigate hypothetical scenarios. However contrary to the expectations, the proposed zero nutrient input scenario (over 50 years) achieves surprisingly minor overall improvements, which are clearly identifiable only in the Adriatic Sea and the Aegean Sea, regions actually suffering from the most pronounced nutrient inputs. This seems to be in line with recent evidence that reduced nutrient inputs often fail to fully reverse the trajectories of ecosystems during eutrophication and this has challenged the assumption that oligotrophication could drive marine ecosystems back to their original condition (Carstensen et al. 2011).

Simulations for the German coastal waters (Baltic Sea) by Schernewski et al. (2015) indicate that nutrient reduction targets of the Baltic Sea Action Plan (HELCOM) might not be sufficient to reach good ecological status in German Baltic coastal waters. Schernewski et al. (2015) stress the observation of strong gradients within water bodies that might require a better spatial differentiation of reference and target values.

The used modelling system for the Mediterranean Sea and the Baltic Sea captures only a small part of the overall ecosystem dynamics and even in that parts remain several weaknesses that require attention and improvement (like the underestimated Chla in the Adriatic Sea). Further the very high importance of the quality as well as spatial and temporal resolution of discharge and nutrient input data (point sources, diffuse and atmospheric) became obvious, the actual available data are not of sufficient resolution and quality.

Incomplete list of remaining open issues and needed future work:

- Open discussion of applied procedure for non-dimensionalisation (applied scaling range)
- Extended comparison to indicators calculated from measured data
- Extending the scenario simulations (considering for example 50% and 200% of nutrient inputs)
- Scenario simulations starting with low nutrient conditions
- Scenario simulations with and without atmospheric nutrient input
- Defining target and reference values for HEAT for the Mediterranean Sea
- Calculating bottom oxygen debt from model data for HEAT
- Using longer ecosystem simulations (especially for the Baltic Sea)
- Investigation of a quasi pristine system state
- Addressing the issue of how to define a base line
- Improvement of discharge and nutrient input data
- Use of several (improved) ecosystem models (ensemble simulations).

In collaboration with the ecosystem group of Institute for Baltic Sea Research (IOW, Thomas Neumann) an evaluation using longer scenario runs for the Baltic Sea based on the IOW ecosystem modelling system is planned.

Despite that changes in climate forcing and hydrographic variability are important factors modulating spatial and temporal eutrophication trends, it is clear that further nutrient reductions in the Mediterranean Sea and in the Baltic Sea will be necessary to reduce the eutrophication impact on marine and coastal ecosystems. However, it seems illusionary to aim at fully restoring past ecosystems, rather ecosystem management should develop iterative adaptation strategies to deal with shifting baselines and to maintain ecosystem services at a sustainable level.

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## List of abbreviations and definitions

aD%O:	deviation of oxygen saturation from 100%
BSAP:	Baltic Sea Action Plan
Chla:	Chlorophyll a
Conf:	Confidence intervall (95%)
D2:	Dewpoint temperature at 2 m [degree Celsius]
DIN:	Dissolved Inorganic Nitrate
DIP:	Dissolved Inorganic Phosphate
ECMWF:	European Centre for Medium term Weather Forecasts
EQR:	Ecological Quality Ratio
ERA40:	40 years climatological reanalysis (by ECMWF)
ERAIN:	Third generation interim climatological reanalysis (by ECMWF)
ERGOM:	Ecological Regional Ocean Model
ER:	Eutrophication Ratio (HEAT)
ES:	Eutrophication Status (HEAT)
GCM:	Global Circulation Model
GETM:	General Estuarine Transport Model
HEAT:	HELCOM Eutrophication Assessment Tool
HELCOM:	Helsinki Commission
Max:	Maximum
Min:	Minimum
N:	Nitrogen
OSPAR:	The Convention for the Protection of the Marine Environment of the North-East Atlantic
P:	Phosphate
PPR:	Primary Productivity Rate
R:	High level programming language: R
R1:	simulation R1_RF_RN (baseline)
R2:	simulation R2_CF_RN
R3:	simulation R3_CF_NO
Rstudio:	Integrated development environment for R
rTRIX:	Version of TRIX indicator using PPR instead of chla
SD:	Secchi Depth
SLP:	Sea level atmospheric pressure [Pascal]
SSA:	Singular Spectrum Analysis
Stdev:	Standard deviation from the mean
T2:	Air temperature at 2m [degree Celsius]



TCC:	Total Cloud Cover
TN:	Total Nitrogen
TP:	Total Phosphor
TRIX:	Trophic Index (trix)
U10:	East component of 10 m wind speed [ $\text{m s}^{-1}$ ]
V10:	North component of 10 m wind speed [ $\text{m s}^{-1}$ ]

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